



**Defense Threat Reduction Agency  
8725 John J. Kingman Road, MS-6201  
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**DTRA-TR-12-017**

# TECHNICAL REPORT

## **Radiation Dose Assessments for the Embryo, Fetus, and Nursing Infant during Operation Tomodachi**

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August 2013

Prepared by:

The Operation Tomodachi Registry, Dose  
Assessment and Recording Working Group

For:

The Assistant Secretary of Defense for Health Affairs

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This report provides assessments for radiation doses to the embryos/fetuses and nursing infants of Department of Defense personnel that were potentially exposed to radioactive material from the Fukushima Daiichi nuclear power station units' radiological releases that followed the earthquake and tsunami on March 11, 2011. The associated Department of Defense disaster relief operation to the citizens of Japan was entitled, "Operation Tomodachi." These radiation dose assessments for the population of interest will be summarized in the Operation Tomodachi Registry to support public inquiries.

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UNIT CONVERSION TABLE			
U.S. customary units to and from international units of measurement*			
U.S. Customary Units	Multiply by 		International Units
	 Divide by†		
<b>Length/Area/Volume</b>			
inch (in)	2.54	$\times 10^{-2}$	meter (m)
foot (ft)	3.048	$\times 10^{-1}$	meter (m)
yard (yd)	9.144	$\times 10^{-1}$	meter (m)
mile (mi, international)	1.609 344	$\times 10^3$	meter (m)
mile (nmi, nautical, U.S.)	1.852	$\times 10^3$	meter (m)
barn (b)	1	$\times 10^{-28}$	square meter (m <sup>2</sup> )
gallon (gal, U.S. liquid)	3.785 412	$\times 10^{-3}$	cubic meter (m <sup>3</sup> )
cubic foot (ft <sup>3</sup> )	2.831 685	$\times 10^{-2}$	cubic meter (m <sup>3</sup> )
<b>Mass/Density</b>			
pound (lb)	4.535 924	$\times 10^{-1}$	kilogram (kg)
atomic mass unit (AMU)	1.660 539	$\times 10^{-27}$	kilogram (kg)
pound-mass per cubic foot (lb ft <sup>-3</sup> )	1.601 846	$\times 10^1$	kilogram per cubic meter (kg m <sup>-3</sup> )
pound-force (lbf avoirdupois)	4.448 222		newton (N)
<b>Energy/Work/Power</b>			
electronvolt (eV)	1.602 177	$\times 10^{-19}$	joule (J)
erg	1	$\times 10^{-7}$	joule (J)
kiloton (kT) (TNT equivalent)	4.184	$\times 10^{12}$	joule (J)
British thermal unit (Btu) (thermochemical)	1.054 350	$\times 10^3$	joule (J)
foot-pound-force (ft lbf)	1.355 818		joule (J)
calorie (cal) (thermochemical)	4.184		joule (J)
<b>Pressure</b>			
atmosphere (atm)	1.013 250	$\times 10^5$	pascal (Pa)
pound force per square inch (psi)	6.984 757	$\times 10^3$	pascal (Pa)
<b>Temperature</b>			
degree Fahrenheit (°F)	[T(°F) – 32]/1.8		degree Celsius (°C)
degree Fahrenheit (°F)	[T(°F) + 459.67]/1.8		kelvin (K)
<b>Radiation</b>			
curie (Ci) (activity of radionuclides)	3.7	$\times 10^{10}$	s <sup>-1‡</sup>
air exposure (roentgen)	2.579 760	$\times 10^{-4}$	coulomb per kilogram (C kg <sup>-1</sup> )
absorbed dose (rad)	1	$\times 10^{-2}$	J kg <sup>-1§</sup>
equivalent and effective dose (rem)	1	$\times 10^{-2}$	J kg <sup>-1**</sup>

\* Specific details regarding the implementation of SI units may be viewed at <http://www.bipm.org/en/si/>.

† Multiply the U.S. customary unit by the factor to get the international unit. Divide the international unit by the factor to get the U.S. customary unit.

‡ The special name for the SI unit of the activity of a radionuclide is the becquerel (Bq). (1 Bq = 1 s<sup>-1</sup>).

§ The special name for the SI unit of absorbed dose is the gray (Gy). (1 Gy = 1 J kg<sup>-1</sup>).

\*\* The special name for the SI unit of equivalent and effective dose is the sievert (Sv). (1 Sv = 1 J kg<sup>-1</sup>).

**DTRA-TR-12-017: Radiation Dose Assessments for the Embryo, Fetus, and Nursing Infant during Operation Tomodachi**

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## Executive Summary

The purpose of this report is to present the approach, methods, and results of an initial study to calculate conservative estimates of radiation doses to embryos/fetuses and nursing infants among the Department of Defense (DOD) Population of Interest (POI) from radioactive material released during the two months following the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS). As discussed in Cassata et al. (2012), this population was in Japan during DOD's Operation Tomodachi (OT) to provide humanitarian assistance and disaster relief to the Japan. The radiation doses presented in this report will be summarized on the Operation Tomodachi Registry (OTR) website (<https://registry.csd.disa.mil/>). This report is a supplement to *Radiation Dose Assessment for Shore-Based Individuals in Operation Tomodachi, Revision 1* (Cassata et al., 2012) and is part of a series of reports undertaken by the DOD to assess radiation doses to DOD-affiliated individuals or characterize the radiological environment at J-Village (a staging area about 20 km south of FDNPS).

This report focuses on those locations where it is more likely that the DOD-affiliated population of known or possibly pregnant women would remain for the entire two month period under consideration. This report presents credible, conservative estimates of the radiation doses to an embryo/fetus or nursing infant at eight specific, shore-based locations where approximately 53,000 DOD-affiliated individuals were located during OT. Estimated radiation doses for women deployed to forward locations (i.e., locations relatively closer to FDNPS and used on a temporary basis) are not included in this report. Radiation doses at all locations depend on, among other things (1) the radiological conditions of the environment, (2) the timing of the exposure (e.g., if a particular individual was present at a given location at the time the arrival of radioactive material and (3) the duration of exposure. Anyone deployed to forward locations during passage of a radioactive plume would have received a higher dose than those who were present at the time other than when the plume was passing. Also, a deployment for one day would likely result in a lower dose than a deployment lasting many days. Assuming an exposure to an embryo/fetus or nursing infant at a forward location that lasted for two months following the start of the accident would result in dose estimates that were unduly large and unrealistic. Scientific Committee 6-8 of the National Council on Radiation Protection and Measurements reviewed this report and concurred that the radiation doses calculated in this report are very conservative, high-sided, estimates and are likely greater than any doses received.

Table ES-1 shows the ranges of doses estimated for an embryo/fetus and nursing infant during Operation Tomodachi at locations where the population was relatively stable; that is, for women who were not deployed to forward locations. The ranges shown in Table ES-1 reflect doses calculated for all credible locations (i.e., excluding forward locations) and a variety of exposure conditions. The highest values in each range were calculated under dose maximizing conditions and are intended to be summarized on the OTR website and assigned by default in the OTR.

**Table ES-1. Estimated radiation doses to an embryo/fetus and a nursing infant during Operation Tomodachi**

<b>Group</b>	<b>Total Effective Dose (mSv [rem])</b>	<b>Thyroid Dose (mSv [rem])</b>
Embryo/fetus	0.01–0.89 [0.001–0.089]	0.04–12 [0.004–1.2]
Nursing Infants	0.02–1.3 [0.002–0.13]	0.04–21 [0.004–2.1]

A probabilistic analysis (Section 5 of this report) was conducted using conditions at Yokota Air Base to evaluate whether the doses reported in Table ES-1 and in Section 3 are high sided and meet the goal of being higher than those that are likely to have been received by a specific embryo/fetus or nursing infant. This analysis confirmed (1) that the methods used to estimate the doses shown in Table ES-1 and in Section 3 are very conservative and (2) that the methods likely resulted in calculated doses greater than the actual dose received by any specific embryo/fetus or nursing infant from radioactive materials released during the FDNPS accident. The radiation doses tabulated in Table ES-1 are higher than the 95<sup>th</sup> percentile values of the probabilistic distributions presented in Section 5.

The doses shown in Table ES-1 are useful for understanding the potential ranges of doses to embryos/fetuses and nursing infants during OT, and they can also be used for hypothesis generation and initial studies of health outcomes. However, the doses should not be used for estimates or studies of radiation risk. The effective dose is a radiation protection quantity and can be broadly indicative of potential risks for a population exposed to radiation; it is not the proper quantity for estimating individual risks. Although the organ doses can, in principle, be used to estimate risks to individuals, the thyroid doses reported here should not be used to estimate individual risks either. The thyroid doses in this report are location-based doses derived from assuming a continuous two-month exposure and a multiplicative factor of three applied to the dose coefficients used to calculate the dose from intakes of radioactive iodine, cesium, and tellurium, hence they are inappropriate for estimating risks to a specific embryo/fetus or nursing infant. The potential radiation risk to a specific embryo, fetus, or nursing infant must have an estimate of the actual dose made by a qualified expert<sup>1</sup>, and this dose must be evaluated in conjunction with a physician who specializes in prenatal or early childhood radiation risks.

For doses less than about 100 mSv (10 rem), risks above the normal risks for birth defects or other adverse pregnancy outcomes have not been seen in people (NCRP, 2013). The implication is that the risks to an embryo/fetus are very small and might possibly be zero. No inherited diseases have been seen in children whose parents were exposed to radiation before conception (NCRP, 2013).

The staff of the DOD Birth and Infant Health Registry<sup>2</sup> (BIHR) has examined available data on identified pregnant women and rates of birth defects during OT. The BIHR staff, for women identified as pregnant, determined the rates of pregnancy loss, live births, and birth defects. Roughly 600 total pregnancies were identified among women in the DOD-affiliated population during the OT period; of these, there were about 560 confirmed live births. For

<sup>1</sup> NCRP (2013) defines a qualified expert for the purposes of its report as “a person having the knowledge and training to measure radiation, to evaluate radiation safety techniques, and to advise regarding radiation protection needs.” The definition also includes a list of the professional certifications required to be a qualified expert.

<sup>2</sup> The DOD Birth and Infant Health Registry was created in 1998 to research the health effects of military service on reproductive health and examine pregnancy outcomes among women with specific exposures. This registry also provides surveillance of births within the DOD to assess health outcomes.

infants (about 520 with enough information to be included in the analysis), the total rate of adverse health outcomes was consistent with historical BIHR data. (Conlin et al., 2013)

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## Section 1.

### Introduction

#### 1.1 Background

This report is a supplement to *Radiation Dose Assessment for Shore-Based Individuals in Operation Tomodachi, Revision 1* (Cassata et al., 2012) and addresses potential radiation doses to the embryo/fetus and infants carried by or nursed by members of the Department of Defense (DOD) Population of Interest (POI), referred to as the DOD-affiliated population, who were subject to exposure to radioactive materials released during the Fukushima Daiichi Nuclear Power Station (FDNPS) accident.

On March 11, 2011, a magnitude 9.0 earthquake occurred off the east coast of Japan (epicenter 38.297°N, 142.372°E and depth of 30 km) about 370 km northeast of Tokyo (USGS, 2013). The earthquake and subsequent tsunami resulted in about 20,000 killed or missing, 5,000 injured, and 131,000 displaced people (USGS, 2013). Damage to infrastructure along the east coast of Japan included about 330,000 buildings, 2,000 roads, 56 bridges, 26 railways (USGS, 2013). The FDNPS suffered a loss of both offsite power and failure of its backup power systems resulting in a station blackout (GOJ, 2011). As a result of the accident, significant amounts of radioactive material were released and were transported in air across Honshu (Japan's main island), carried out to sea, and deposited on land, buildings and bodies of water on Honshu (INPO, 2011).

At the time of the earthquake, the United States DOD had about 40,000 Service members stationed in all of Japan along with 43,000 dependents, 5,000 DOD civilian employees, and 25,000 Japanese workers (Feickert and Chanlett-Avery, 2011; USFJ, 2013). Of these, about 70,000 individuals affiliated with the DOD POI (called "DOD-affiliated population" hereafter, and defined as Service members, civilian employees, family members of Service members and civilian employees, and contractor employees) lived and worked at or near 63 sites on the four main islands of Japan (Hokkaido, Honshu, Shikoku, and Kyushu) with the majority of this population located in six military facilities/bases in the Tokyo prefecture (~240 km from FDNPS). In response to the disaster, DOD implemented Operation Tomodachi (OT) to provide humanitarian assistance and disaster relief (HADR) to Japan. Fifteen military facilities/bases were located in Kanagawa prefecture (~260 km from FDNPS), and 10 military facilities/bases were located in Nagasaki prefecture (~1100 km from FDNPS). About half of the DOD-affiliated, shore-based population in Japan was not included in this assessment because the members were located in the Okinawa prefecture, where observed radiation levels did not rise above background levels. The Operation Tomodachi Registry's (OTR's) Dose Assessment and Recording Working Group (DARWG) noted that DOD-affiliated individuals were concentrated at certain sites located throughout Japan, and so the DARWG created 14 broad-based locations (called DARWG locations<sup>3</sup>) encompassing the 63 sites so that a location-based dose estimate could be prepared for each location (Cassata et al., 2012). The approach taken is intended to

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<sup>3</sup> A brief discussion of the DARWG locations can be found in Appendix B.

ensure that the estimated doses would be representative of each location. Section 3 of Cassata et al. (2012) contains the detailed discussions of the development of the potentially exposed populations (PEPs), and the construction of the 14 DARWG locations.

Cassata et al. (2012) provides details on the accident, DOD's response and presence in Japan, environmental data and monitoring, dose calculations and data use, discussion about the quality assurance efforts both in data collection and the DARWG work, a summary and discussion of both the whole body effective dose and the equivalent dose to the thyroid for children and adults. Also discussed are the radiation detection instruments used, external and internal radiation monitoring efforts, and population lifestyle data used in the dose calculations. Cassata et al. (2012) provides the technical basis for the OTR doses that are summarized on the OTR website (<https://registry.csd.disa.mil/otr>).

This report is part of a series of reports undertaken by the DOD to assess radiation doses to DOD-affiliated personnel or characterize the radiological environment at J-Village (a sports complex about 20 km from the FDNPS and used as a staging area for visitors to the Fukushima area). These reports include:

- *Radiation Dose Assessments for Shore-Based Individuals in Operation Tomodachi, Revision 1* (DTRA-TR-12-001 (R1)).
- *Probabilistic Analysis of Radiation Doses for Shore-Based Individuals in Operation Tomodachi* (DTRA-TR-12-002).
- *Radiation Internal Monitoring by In Vivo Scanning in Operation Tomodachi* (DTRA-TR-12-004).
- *Radiation Dose Assessments for the Embryo, Fetus, and Nursing Infant during Operation Tomodachi* (DTRA-TR-12-017). [This report]
- *Radiation Doses for Fleet-Based Individuals in Operation Tomodachi* (DTRA-TR-12-041).
- *Characterization of the Radiological Environment at J-Village during Operation Tomodachi* (DTRA-TR-12-045).
- *Comparison of Radiation Dose Studies of the 2011 Fukushima Nuclear Accident Prepared by the World Health Organization and the U.S. Department of Defense* (DTRA-TR-12-048).
- *Operation Tomodachi Registry Environmental Radiation Data Compendium* (DTRA-TR-13-044).
- *Standard Methods (SM) and Standard Operating Procedures (SOPs) for Responding to Operation Tomodachi Individual Dose Assessments and Responding to VA Radiogenic Disease Compensation Claims* (AIPH SM/SOP).

## **1.2 Purpose and Scope of this Report**

The purpose of this report is to present the approach, methods, and results of a study to estimate conservatively high radiation doses that are likely greater than the radiation dose received by any specific embryo/fetus (Section 3) or nursing infant (Section 4) from radioactive materials released during the FDNPS accident. The radiation doses from releases of radioactive material during the FDNPS accident are calculated based on an assumed exposure period of two

months from March 12 to May 11, 2011. This two-month period is based on a previous DARWG analysis (DARWG, 2011) and is discussed in Cassata et al. (2012).

According to the National Council on Radiation Protection and Measurements (NCRP) in *Radiation Dose Reconstruction: Principles and Practices*, “It is necessary to view dose reconstruction as a *process* that begins with a defined purpose and is carried out in a logical and orderly manner (NCRP, 2009a).” This report can be considered a step in the dose reconstruction process.

The scope of this report includes an assessment of radiation doses during the two-month period from March 12, 2011 to May 11, 2011 for the following groups of the DOD shore-based POI:

- “offspring (embryo, fetus, and newborn child)” from intakes of radioactive material by the mother (ICRP, 2001a) and
- infants including contributions from the ingestion of mother’s milk and an infant’s exposure to external sources of radiation from radionuclides in the mother.

Also included in the scope of this report are:

- A brief discussion of radiological quantities and units (Appendix A);
- A short summary of how and why the DARWG locations were created (Appendix B);
- A table and brief discussion of parameter values to account for different lifestyles (Appendix C);
- A brief assessment of potential radiation doses accrued by the embryo/fetus and nursing infant after May 11, 2011 (Appendix D); and,
- A discussion of uncertainties in dose per unit intake values (Appendix E).

This report does not address:

- Regulatory issues or the traditional areas of radiation safety or protection.
- Personal actions that might have reduced radiation doses.
- Radiogenic risks of adverse health effects.

### **1.3 Overview of the Dose Assessment**

The quantities calculated in this report are the whole body effective dose and the equivalent dose to the thyroid (called the thyroid dose in this report) as defined in ICRP Publication 60 (ICRP, 1991) and used in the ICRP databases of dose coefficients (DC) (ICRP, 2001b; 2003a; 2007b). The effective dose is a radiation protection quantity that allows external and internal radiation doses to be combined. It is not routinely used in retrospective dose assessments other than for comparisons with dose limits or action levels (ICRP, 2007a); however, the effective dose is useful in a preliminary assessment (NAS, 1995). Appendix A contains a brief explanation of the radiological quantities and units used in this report.

Conceptually, the radiation doses to the embryo/fetus or nursing infant from the mother's inhalation of air and ingestion of water and soil are calculated by multiplying the breathing and ingestion rates of the mother by the radionuclide concentration in a given medium to get the amount of the radionuclide taken into the mother's body per unit time (intake rate). For a nursing infant, the infant's air inhalation and water and soil ingestion are also accounted for by using the infant's intake rates as shown in Cassata et al. (2012). This intake rate (whether by inhalation or ingestion), is multiplied by a DC to calculate the dose rate to the embryo/fetus or nursing infant. It is this dose rate that is summed over the two-month OTR exposure period.

An OTR exposure period of two months was chosen based on a review of the environmental radiation data available to the DARWG in 2011 (Cassata et al., 2012). These data were used to estimate preliminary total effective doses that would accrue during a year following any given day from exposure to the environmental conditions on that day. The calculations were performed for Yokota Air Base (AB) and Yokosuka Naval Base (NB). For the year following May 11, 2011, the total effective dose increased by less than 0.01 mSv (0.001 rem) during that period. The full explanation for the derivation of the two-month OTR period can be found in DARWG (2011).

The dose to the embryo and fetus depends strongly on the exposure of the mother to both internal and external sources of radiation. Therefore, the potential radiation exposure of women who were pregnant or might have become pregnant during Operation Tomodachi (OT) was considered because intakes during pregnancy or during the two-month period that might affect a subsequent pregnancy are of concern. To assess the radiation dose from the ingestion of mother's milk, nursing infants are considered to be less than 12 months old<sup>4</sup>. Data from the Defense Manpower Data Center showed (as of July 16, 2012) that there were 1,082 infants in this age group in the POI (Maranville, 2012). Intakes of radionuclides by nursing mothers are of concern because it is their intakes that result in radionuclides passing to the infant from mother's milk.

High-sided estimates of the inhalation rates, ingestion rates, and time spent outdoors (See Appendix C for the values used.) were used to calculate the doses in this report. Because high-sided parameter values were used, the doses in this report are theoretically possible but not likely to be received by any individual. The methods account for exposure while performing at various levels of physical activity, whether indoors or outdoors. Environmental radiation data collected by the DOD, the Department of Energy (DOE), the Government of Japan (GOJ) and others were evaluated (Cassata et al., 2012) as part of the dose assessment process. Data were either used as reported or appropriate values were estimated using scientifically-sound techniques (Cassata et al., 2012) for those periods where data were not available or when data were judged unreliable.

#### **1.4 The DOD Birth and Infant Health Registry**

The DOD Birth and Infant Health Registry (BIHR) was created in 1998 to research the health effects of military service on reproductive health and examine pregnancy outcomes among women with specific exposures. This registry allows for surveillance of births within the DOD to assess health outcomes. The BIHR serves to address<sup>5</sup> "the reproductive health concerns of

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<sup>4</sup> This age was chosen for a U.S. population based on information in chapter 15 of EPA (2011).

<sup>5</sup> See <http://www.med.navy.mil/sites/nhrc/Pages/Department164.aspx> (accessed May 25, 2013).

military families with strong science and surveillance, contributing to progress in the prevention of birth defects and other infant health challenges.”

The BIHR was asked by the OTR Medical and Claims Users Working Group to investigate “outcomes among an identified population of women captured in the OTR who were thought to be pregnant around the time of the radiation incident” (Conlin et al., 2013). Five hundred and eighty-eight women were identified as being pregnant during the OTR period or who had pregnancy care ending within a 30-day period before March 11, 2011 (Conlin et al., 2013). There were 590 pregnancies among these 588 women with about 72 percent among military dependents, 22 percent among military sponsors, and the remaining 6 percent to non-military individuals (Conlin et al., 2013).

The pregnancy outcomes identified by Conlin et al. (2013) are “live delivery,” “spontaneous loss,” and “induced abortion,” with the remaining outcomes listed as “unknown” likely because “eligibility for care ending prior to the pregnancy outcome and/or lack of visibility of a pregnancy outcome in the electronic medical data/records.” The live delivery and spontaneous loss rates were quite favorable; that is, the live delivery rate was high and the spontaneous loss rate was low. If the data are limited to those pregnancies that began during the OTR period, then the loss rate was about 13 percent (10 losses out of 76 total deliveries), which is in the range of 10–20 percent expected for the U.S. population (Conlin et al., 2013). However, this population might not be representative of the equivalent population within the POI because the “identified population of women” preferentially included women who sought prenatal care and had progressed beyond the point in a pregnancy where spontaneous loss most often occurs (Conlin et al., 2013). Conlin et al. (2013) also examined the live births of 523 infants for whom there was enough identifying information to be included in an analysis of health outcomes and found that the rates of birth defects, prenatal growth problems, and premature birth were comparable to the 520 live births in the BIHR for “infants included if gestation occurred at any time during the 11MAR2009 – 10MAY2009 [sic] window.”

Conlin et al. (2013) reported that more work is being planned to identify women who might have been in the area during the OTR period but were not included in the initial analyses; to identify other births in Japan whose dates would indicated conception before or on March 11, 2011; and, to identify women who sought or had pregnancy-related or other medical care and subsequent were pregnant or gave birth elsewhere that could be associated with the OTR. Longitudinal studies with follow-up periods of one year or more are being planned for live-born infants (Conlin et al., 2013).

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## Section 2.

### Basic Dose Model and Common Parameters

#### 2.1 Basic Dose Model

The basic dose model for calculations of radiation dose is similar to that presented in Cassata et al., (2012). Calculations are carried out for a hypothetical population that includes women (pregnant or who might become pregnant), their embryos/fetuses, and nursing infants. The model assumes that the embryo/fetus:

- Is irradiated by external sources of radiation, and
- Receives a radiation dose from radionuclides inhaled or ingested by the mother.

The radiation dose to the embryo/fetus is the sum of the radiation dose from radiation sources outside the mother (external radiation), radionuclides within the mother (including the placenta), and radionuclides within the fetus. The latter two sources are accounted for in the models used to develop DCs for the embryo/fetus dose calculations (ICRP, 2001a). For this report, it is assumed that external dose to the embryo/fetus from environmental sources of radiation is equal to that received by the mother. For the assessment of internal radiation doses to an embryo or fetus, intakes by the mother are of concern. Intakes by the mother are also important for the doses to nursing infant because of transfers to the mother's milk and subsequent ingestion of milk by the infant.

The total radiation dose received by the embryo/fetus is the sum of radiation doses from sources outside (external) and inside (internal) the body as summarized conceptually in equation (1).

$$TED = E_{\gamma} + E(\tau)_{inh} + E(\tau)_w + E(\tau)_s \quad (1)$$

where:

$TED$  = Total whole body effective dose to the embryo/fetus (mSv).

$E_{\gamma}$  = Effective dose from external radiation (mSv).

$E(\tau)_{inh}$  = Committed effective dose from inhalation by the mother (mSv).

$E(\tau)_w$  = Committed effective dose from water ingestion by the mother (mSv).

$E(\tau)_s$  = Committed effective dose from soil ingestion by the mother (mSv).

$\tau$  = Time period during which an internal dose is calculated.

For a nursing infant, the situation is somewhat different. In addition to the external and internal radiation doses received from the environment, a nursing infant is also exposed to radionuclides in mother's milk and to a lesser extent external radiation from radionuclides in the mother's body. This is shown conceptually in equation (2).

$$TED = E_{\gamma} + E(\tau)_{inh} + E(\tau)_W + E(\tau)_S + E(\tau)_{MM} + E_{M\gamma} \quad (2)$$

where:

$TED$	=	Total whole body effective dose to a nursing infant (mSv).
$E_{\gamma}$	=	Effective dose from external radiation from the environment (mSv).
$E(\tau)_{inh}$	=	Committed effective dose from inhalation by a nursing infant (mSv).
$E(\tau)_W$	=	Committed effective dose from water ingestion by a nursing infant (mSv).
$E(\tau)_S$	=	Committed effective dose from soil ingestion by a nursing infant (mSv).
$E(\tau)_{MM}$	=	Committed effective dose from ingestion of mother's milk by nursing infants (mSv).
$E_{M\gamma}$	=	Effective dose from external radiation from radionuclides in the mother (mSv).
$\tau$	=	Time period during which an internal dose is calculated.

The last two terms in Equation (2) represent the internal radiation dose to a nursing infant from the ingestion of mother's milk and the external radiation dose from radionuclides in the mother's body. In Section 4.5, it is shown that the external radiation dose to a nursing infant from radionuclides in the mother's body is small compared to other sources of radiation dose.

The equivalent dose to the thyroid (or any organ or tissue) can be calculated by summing the equivalent doses from all sources of radiation in the same manner as in Equation (1) and equation (2). In the above equations,  $\tau$  is "the integration time in the years following the intake" (ICRP, 2007a) and accounts for transport and decay of radionuclides taken into the body" and should not be confused with a variable of time such as  $t$  used in Section 5. For the embryo, fetus, and nursing infants, this integration time is to age 70. See Appendix A, Section A-5 for more details about committed doses and the other radiological quantities and units used in this report.

In practice, the total dose is calculated by summing the hourly dose rates over the two-month OTR exposure period. Conceptually, the radiation doses (to the embryo/fetus or nursing infant) from inhalation and ingestion (water and soil by the mother) are calculated by multiplying the breathing and ingestion rates of the mother by the radionuclide concentration in a given medium to get the amount of the radionuclide taken into the body per unit time (intake rate). This intake rate (whether by inhalation or ingestion), is multiplied by the appropriate DC to calculate the dose rate to the embryo/fetus or nursing infant. It is this dose rate that is summed over the two-month OTR exposure period. The details of the calculations used to calculate radiation doses are discussed in Cassata et al. (2012).



The radiation dose for a specific embryo/fetus or nursing infant exposure cannot be easily characterized because of a strong dependence of dose on the stage of embryonic and fetal development (NCRP, 1998a). For radionuclides deposited in the body, generalizations about radiation dose are further complicated because some radionuclides might cross the placenta, non-random distribution of radionuclides in the embryo/fetus, individual differences in radionuclide metabolism, and exponentially changing dose rates (Brent, 1992). Also, because of the mobility of the population during the OTR exposure period and the temporal variation of the releases, the timing of exposure is critical in determining the radiation dose. Because of these factors, doses to a specific embryo/fetus or nursing infant should be evaluated on an individual basis.

## **2.2 Common Parameters**

Because the calculations of radiation dose to the embryo/fetus and nursing infant are based on external radiation dose to the mother and the intakes of radioactive material by the mother, the calculations share the following common parameters: external radiation dose rates, radionuclides of concern, radionuclide physical and chemical properties, mothers' intake rates, and uncertainties in the DCs.

### **2.2.1. External Radiation Dose Rates**

Both the embryo/fetus and nursing infant are assumed to receive the same external radiation dose received by the mother. The external radiation dose rates were calculated from data compiled from DOD, DOE, and Ministry of Education, Culture, Sports, Science, and Technology (MEXT) sources<sup>6</sup>, which were examined for transcription errors and anomalously high or low values; and, finally, adjusted to increase MEXT external radiation dose rates to account for an apparent low bias in the MEXT data when compared to DOE and DOD data (Cassata et al., 2012). An example for Yokosuka NB is shown in Figure 1.

### **2.2.2. Radionuclides of Concern**

The radionuclides to which women were exposed during the OTR period are described in Cassata et al. (2012). That report contains a detailed discussion of radionuclide concentrations in all environmental media (except for food for reasons discussed in Section 2.7, Food Monitoring, of Cassata et al. [2012]). The radionuclides of concern identified in Table C-1 of Cassata et al. (2012) have been adopted in this report and are shown in Table 1.

### **2.2.3. Physical and Chemical Properties of Radionuclides**

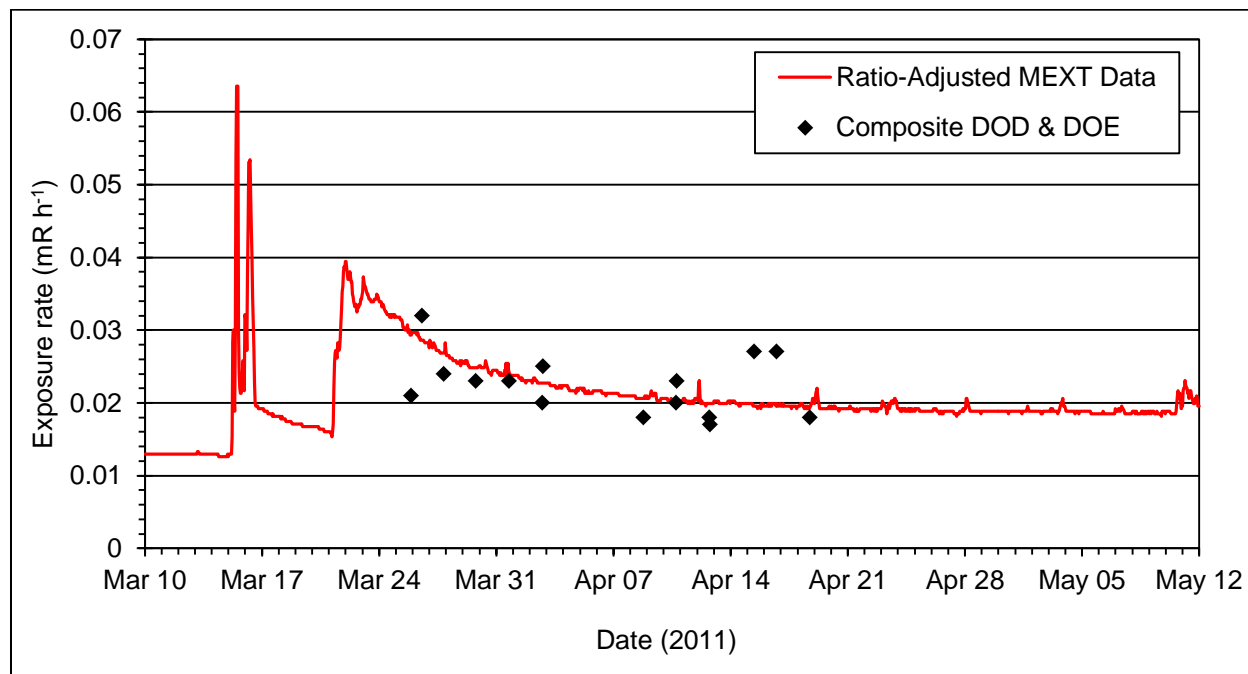
The physical and chemical properties of the radionuclides used for this analysis are as follows (Cassata et al., 2012):

- All airborne radionuclides were present only as aerosols, except for iodine for which:
  - Iodine was present in both gaseous and aerosol forms;
  - Time and concentration-weighted gas-to-aerosol ratio was determined to be 2.51;
  - One-third of the gaseous iodine was assumed to be in elemental form (I<sub>2</sub>) and two-thirds was in organic form (methyl iodide); and,

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<sup>6</sup> Data are reported in the original units used by the organization that gathered the data under the assumption that exposure rates and dose rates are equivalent.

- All aerosols were assumed to be of absorption type F<sup>7</sup> and to have a 1  $\mu\text{m}$  activity median aerodynamic diameter (AMAD).



**Figure 1. Composite DOD and DOE, and adjusted MEXT exposure rates at Yokosuka NB**

#### 2.2.4. Mother's Intake Rates

To ensure that potential intakes were not underestimated and to account for unknown pregnancies occurring near the time of exposure, intake scenarios (see Sections 3.5 and 4.4) were chosen to maximize dose estimates to the embryo/fetus and nursing infant. For the embryo/fetus, the approach assumes that the entire dose of radiation occurred during a single (acute) exposure to external radiation and intake of radioactive materials occurring 35 weeks after conception, and for the nursing infant a single, acute exposure and intake one week after birth. It was also assumed both these scenarios exclude female Service members who were engaging in HADR<sup>8</sup> efforts. According to EPA (2011), the 95<sup>th</sup> percentile values for the physiological daily inhalation rates for pregnant women (underweight, normal-weight, and overweight) at the 36<sup>th</sup> week of pregnancy range from about 26 to 35  $\text{m}^3 \text{d}^{-1}$  with a mean of about 30  $\text{m}^3 \text{d}^{-1}$ . Similarly, for post-partum (6<sup>th</sup> week) women the inhalation rates range from about 25 to 31  $\text{m}^3 \text{d}^{-1}$  with a mean of about 28  $\text{m}^3 \text{d}^{-1}$  (EPA, 2011). The overall mean 95<sup>th</sup> percentile inhalation rates for both pregnant and post-partum women are about 28  $\text{m}^3 \text{d}^{-1}$ . For ingestion rates of “community water” the EPA (2011) recommends  $\sim 2.6 \text{ L d}^{-1}$  and  $\sim 3.6 \text{ L d}^{-1}$  for pregnant and lactating women, respectively. Overall, these inhalation and water ingestion rates for women of childbearing age and to nursing

<sup>7</sup> Type F material is defined by the ICRP (2012) as “those materials that are readily absorbed into blood from the respiratory tract (fast rate of absorption).”

<sup>8</sup> HADR efforts include physically demanding activities, such as loading and unloading supplies, cleaning operations such as shoveling, sweeping, and hauling debris, and construction, carried out for longer durations than normal.

**Table 1. Radionuclides considered in calculations of internal dose**

<b>Air Inhalation<sup>*,†</sup></b>	<b>Water Ingestion</b>	<b>Soil Ingestion</b>
Ba-140 ( $t_{1/2}$ = 12.78 d)	I-131 ( $t_{1/2}$ = 8.04 d)	I-131 ( $t_{1/2}$ = 8.04 d)
Cs-134 ( $t_{1/2}$ = 2.05 y)	Cs-134 ( $t_{1/2}$ = 2.05 y)	Cs-134 ( $t_{1/2}$ = 2.05 y)
Cs-136 ( $t_{1/2}$ = 13.70 d)	Cs-137 ( $t_{1/2}$ = 30.0 y)	Cs-136 ( $t_{1/2}$ = 13.70 d)
Cs-137 ( $t_{1/2}$ = 30.0 y)		Cs-137 ( $t_{1/2}$ = 30.0 y)
I-130 <sup>‡, **</sup> ( $t_{1/2}$ = 0.51 d)		Te-132 ( $t_{1/2}$ = 3.25 d)
I-131 ( $t_{1/2}$ = 8.04 d)		
I-132 ( $t_{1/2}$ = 0.09 d)		
I-133 ( $t_{1/2}$ = 0.84 d)		
La-140 <sup>**</sup> ( $t_{1/2}$ = 40.18 h)		
Rb-86 <sup>**</sup> ( $t_{1/2}$ = 18.63 d)		
Mo-99 ( $t_{1/2}$ = 2.78 d)		
Tc-99m ( $t_{1/2}$ = 6.05 h)		
Te-129 <sup>**</sup> ( $t_{1/2}$ = 0.05 d)		
Te-129m ( $t_{1/2}$ = 33.97 d)		
Te-131m ( $t_{1/2}$ = 1.25 d)		
Te-132 ( $t_{1/2}$ = 3.25 d)		
Sr-89 <sup>§</sup> ( $t_{1/2}$ = 52.60 d)		
Sr-90 <sup>§</sup> ( $t_{1/2}$ = 27.70 y)		

\* " $t_{1/2}$ " represents the radiological half-life of the radionuclide.

† All radionuclides are in aerosol form only except radioiodines, which may be present in gaseous or aerosol forms. The hourly activity concentrations for gaseous radioiodines were calculated by multiplying the corresponding aerosol concentration by 2.51, a factor determined from DOD airborne activity concentration measurements on 12 days during March 16 through April 30, 2011 at Yokosuka NB, Yokota AB, and the U.S. Embassy. Gaseous iodine was assumed to consist of 1/3 elemental form ( $I_2$ ) and 2/3 organic form (methyl iodide) (Cassata et al., 2012).

‡ Although I-130 is not a fission product, it is produced by neutron activation in a power reactor in sufficient quantities, and it was measured in air samples (Cassata et al., 2012).

§ The hourly values for these radionuclides were calculated by multiplying the Cs-137 air activity concentration by 0.00053. This factor is the mean value ( $n = 15$ ) of the Sr-90 to Cs-137 ratio taken from a set of soil analyses from a May 31, 2011 MEXT soil analysis report (GOJ, 2011).

\*\* Because of the low concentrations and small DCs (Table E-1) of these radionuclides, they were not used in the calculations of radiation doses.

mothers are best approximated by the rates assumed for adults engaged in routine activities (Cassata et al., 2012). The following intake rates were used as the maximum exposure conditions for this analysis:

- Inhalation Rate:  $30 \text{ m}^3 \text{ d}^{-1}$ ;
- Drinking Water Ingestion Rate:  $4 \text{ L d}^{-1}$ ; and,
- Soil Ingestion Rate:  $200 \text{ mg d}^{-1}$ .

## 2.2.5. Adjustment for Uncertainties in Dose Coefficients

The purpose of this report is to describe radiation doses that are likely greater than the dose received by any specific embryo/fetus. The DARWG did not attempt to prepare best (or

central) estimates of doses and their associated uncertainties; however, to ensure conservatism, or high-sidedness, an adjustment factor of three was applied to the DCs for cesium, iodine (all forms), and tellurium used to calculate both the committed effective doses and committed equivalent doses to the thyroid for the embryo/fetus and nursing infant; that is, the DCs were multiplied by a factor of three in the spreadsheets used to calculate the doses. Based on a literature review of the information on the uncertainty in radiation doses from the intakes of radionuclides, this adjustment factor was established from the conclusion that an uncertainty factor<sup>9</sup> (UF) of three is representative for these exposures. Appendix E discusses this analysis of DC uncertainties.

### **2.2.6. Selection of Parameter Values**

This report provides conservatively high radiation dose estimates that are likely greater than the actual radiation dose received by any specific embryo/fetus or nursing infant. To ensure that the calculated radiation doses are conservative, high-sided values at the upper end of the exposure parameter distributions were chosen, and it was assumed the exposed pregnant or nursing women were outdoors 24 hours each day for the entire two-month OTR period (e.g., exposed to outdoor concentrations of radionuclides in air, exposure rates with no shielding from buildings, etc.). In addition to the radiation dose calculations under dose maximizing conditions for use in the OTR, the DARWG considered more realistic parameter values as well. See Appendix C for a summary of these more realistic parameter values; all parameter values are discussed in detail in Appendix B of Cassata et al., (2012).

### **2.2.7. Locations and Timing of Potential Exposures**

The DARWG locations were created to allow location-based dose estimates for each potentially exposed population (PEP) (Cassata et al., 2012) assuming a two-month exposure at a given location (see Appendix B for details). There were no DOD-affiliated individuals permanently located in areas associated with DARWG locations D-2 through D-7<sup>10</sup> (i.e., Sendai Airport (D-2, Miyagi Prefecture), City of Ishinomaki (D-3, Miyagi Prefecture), City of Yamagata (D-4, Yamagata Prefecture), and City of Oyama (D-7, Tochigi Prefecture) for the entire two-month duration covered by the OTR. These locations tended to be staging or support areas for HADR operations; work locations such as ammunition depots, communication sites, petroleum, oil, and lubrication depots; and various storage and training areas (Cassata et al., 2012). Radiation doses for children at Hyakuri AB (D-6, Ibaraki Prefecture) were included in Cassata, et al. (2012) because Japanese self-defense forces and U.S. forces were co-located there; and, although it was thought unlikely that children were present their absence could not be confirmed.

In actuality, the timing of releases and their subsequent transport and dispersion are critical to the radiation doses and are linked to the people's locations. Most of the radiation dose arises from the plumes of radioactive material, with radiation exposure from residual deposited material being of lesser importance. That is, for individuals to have received the highest doses, they would need to have been at a location and time to be exposed to a passing plume of

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<sup>9</sup> The UF is the square root of the ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values of a given distribution of DCs; this is also equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median) values of a distribution or it can be calculated from a geometric standard deviation, if reported.

<sup>10</sup> Location D-5 is J-Village, which is discussed in McKenzie-Carter et al. (2013).

radioactive materials. The releases responsible for most of the radiation dose occurred between March 12–22, 2011, and of these, the primary releases were March 12–17, 2011, with the first U.S. forces moving to Sendai Airport on March 14, 2011 (Cassata et al., 2012). Personnel arriving after the passage of radioactive plumes from the primary releases would have received much lower doses than they would have if they had been present at these forward locations during the arrival of these plumes. Related to the timing of exposures is the choice of DCs used to calculate the doses to an embryo/fetus or nursing infant. As shown in Section 3 and Section 4, the DCs were chosen to maximize the doses and are assumed to be constant over the two-month OTR exposure period. For the embryo/fetus, the DCs were chosen for intakes occurring 35 weeks after conception; for the nursing infant the DCs were chosen for an infant 1 week of age. Although appropriate for the relatively stable populations at locations located in the Kanagawa, Nagasaki, Tokyo, and other more distant prefectures, these DCs are not credible for forward-deployed women.

Based on the forgoing discussions in this section, estimated doses for DARWG locations D-2 through D-7 are not presented in this report. However, women who might have been deployed to these locations in support of HADR operations at locations and later were found to be pregnant involve a unique exposure situation that might require an individual exposure assessment.

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## **Section 3.**

### **Radiation Doses to an Embryo and Fetus**

#### **3.1 Potentially Exposed Population: the Embryo and Fetus**

In this case, a member of this PEP is any embryo or fetus in utero between March 12 and May 11, 2011. To calculate the radiation dose to the embryo or fetus it is necessary to evaluate the mother's external radiation exposure and intakes of radioactive material.

Because the date of conception for a specific embryo or fetus is difficult to determine, the date of birth was used to restrict the applicability of the results of this report to births occurring between March 12, 2011 and March 6, 2012, including children born to members of the DOD-affiliated population but who were born elsewhere. The date of March 6, 2012 corresponds to 300 days after the end of the assumed exposure period (May 11, 2011). Three hundred days represents, if not an absolute limit, a reasonable limit on the duration of a human pregnancy<sup>11</sup>. Using the period March 12, 2011 through March 6, 2012 ensures that no births from conceptions on or after May 12, 2011 are included in the registry. That is, if a woman conceived after the OTR period, the results of this analysis are not applicable to her newborn, and the newborn will not be in the OT registry. The dose to the embryo/fetus from exposure after May 12, 2011 is likely to be less than about 0.5 mSv as discussed in Appendix D.

#### **3.2 Embryonic and Fetal Development**

The terms used to describe the development of the embryo and fetus vary, but in studies relating to radiation exposure three broad categories of pregnancy are used: pre-implantation, embryonic (organogenesis), and fetal (organ growth) (ICRP, 2001a). During about the first week after fertilization, the zygote continues to develop and travels down the fallopian tube (pre-implantation) and implants in the uterine wall on about the sixth day. Once implanted, the embryonic stage of major organogenesis begins. This stage lasts about eight weeks. The beginning of the ninth week starts the fetal period of organ growth. A detailed discussion of embryonic and fetal development can be found in ICRP Publication 88 (ICRP, 2001a) and at MedlinePlus (<http://www.nlm.nih.gov/medlineplus/ency/article/002398.htm>, accessed June 15, 2012).

#### **3.3 Sources of Radiation Exposure**

The radiation dose to an embryo or fetus arises from the following sources: external radiation dose from the environment and intakes of contaminated air, water, and soil by the mother. The radiation dose from intakes by the mother includes a radiation dose from radionuclides within the mother but outside the fetus (e.g., gamma-ray photons emitted by Cs-137 in the mother's body) and radionuclides that deposit within a fetus (e.g., the dose to a

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<sup>11</sup> Pregnancies longer than 42 weeks beyond the first day of the last menstrual period are associated with risks to both the mother and fetus. After 41 to 42 weeks of gestation most healthcare providers will induce labor. (Source: <http://www.uptodate.com/contents/postterm-pregnancy-beyond-the-basics>, accessed July 14, 2012.)

fetal thyroid from I-131 that has been incorporated into the fetal thyroid). This report presents the results of calculations to estimate conservative values of the radiation dose to the embryo or fetus from all sources of radiation.

### **3.4 Dose Coefficients for the Embryo and Fetus from Intakes of Radionuclides by the Mother**

A detailed discussion of the derivation of the DCs and the radiation doses to the embryo and fetus can be found in ICRP Publication 88 (ICRP, 2001a), Stather et al. (2003), and Phipps et al. (2003). ICRP (2001a) states:

New biokinetic and dosimetric models for calculating doses to the developing embryo and fetus are developed and used in conjunction with the models for infants, children, and adults presented in the previous reports. The models used take account of transfer of radionuclides across the placenta, distribution and retention of radionuclides in fetal tissues, growth of the fetus, and photon irradiation from radionuclides in the placenta and maternal tissues. Human and animal data are used as available in the development of these models. Intake scenarios comprising single or continuous maternal intakes are taken into account in the compilation of effective dose coefficients following ingestion or inhalation of the radionuclides considered. A CD-ROM [ICRP CD-ROM 2 (ICRP, 2003a)] with more comprehensive information on doses from inhalation of different particle sizes, tissue doses, and doses at various times after birth has been developed concurrently with the report and will be available shortly.

The report does not consider doses to the offspring due to intakes of radionuclides in maternal milk and external irradiation from the mother's body after birth. The radiation sensitivity of the offspring is not discussed.

In the development of the biokinetic and dosimetric models for the embryo and fetus, the ICRP combined pre-implantation and embryonic periods and assumed that the committed dose to the embryo was equal to the committed dose (first eight weeks of gestation) to the uterine wall (ICRP, 2001a). The committed effective dose (9<sup>th</sup> to 38<sup>th</sup> week of gestation) to the fetus was calculated separately (ICRP, 2001a). The ICRP (2001a) calls this combined committed effective dose during gestation as the "prenatal committed effective dose." To account for effective dose arising from residual radioactive material in an infant after birth, the ICRP calculated the postnatal committed effective dose to age 70 y. The sum of the prenatal committed effective dose and postnatal committed effective dose is called the "offspring total committed effective dose" (ICRP, 2001a). The offspring total committed effective dose therefore includes only the radiation dose arising from intakes of the mother before birth and does not include any external radiation dose received by an infant after birth, or any internal radiation dose received by an infant from the infant's intakes after birth. Doses to infants from the ingestion of mothers' milk are considered in ICRP Publication 95 (ICRP, 2004).



The ICRP (2001a) developed values of DCs for a limited number of intake scenarios and radionuclide parameters. In the subsequent CD-ROM 2 (ICRP, 2003a), intake scenarios and radionuclide parameters were expanded to include:

- Thirty-one elements
- Members of the public and workers
- Inhalation of aerosols and vapors
- Ingestion
- Five postnatal integration periods
- Ten aerosol sizes
- Seventeen organ doses, remainder organ doses, and effective doses
- Three chronic intake scenarios
- Eight acute intake scenarios.

The DCs used in calculations of committed effective dose and committed equivalent dose were taken from the following ICRP database:

ICRP CD-ROM 2: embryo and fetus; “contains committed equivalent doses per unit intake (DCs) to various tissues and committed effective doses per unit intake (DCs). Results are given for both workers and members of the public. [This distinction accounts for different patterns of aerosol deposition in the lungs.] Results are consistent with the latest ICRP advice given in Publication 88. The database extends the results given in the Publication to include DCs for ten aerosol sizes and for five post natal times after intake.” (ICRP, 2003a)

The following radionuclides are not included in the ICRP databases of DCs for the embryo/fetus: I-130, La-140, Rb-86, and Te-129. No explanation was found for the exclusion of these radionuclides from the ICRP database. However, Mr. Timothy Fell<sup>12</sup> of the U.K. Health Protection Agency provided embryonic and fetal DCs for both effective and thyroid doses (Fell, 2012). These DCs were incorporated in the spreadsheets used to perform the dose calculations.

### **3.5 Intake Scenarios for the Embryo/Fetus**

#### **3.5.1. Introduction**

For this analysis of the radiation doses to the embryo and fetus resulting from intakes during OT, the radionuclides of concern (Section 2.1), their physical and chemical properties (Section 2.2.3), and intake rates (Section 2.2.4) have been established. Some flexibility is introduced by analyzing 11 potential intake scenarios (eight acute and three chronic) as defined by the ICRP (ICRP, 2003a: CD-ROM 2). The scenarios are as follows:

1. Acute intake (1 Bq) 2.5 years prior to conception

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<sup>12</sup> Mr. Fell is a member of the ICRP Committee 2 Task Group on Dose Calculations (DOCAL) and has collaborated on developing specific biokinetic models for the transfer of radiostrontium to the fetus and breast-feeding infant.

2. Acute intake (1 Bq) 6 months prior to conception
3. Acute intake (1 Bq) at conception
4. Acute intake (1 Bq) 5 weeks after conception
5. Acute intake (1 Bq) 10 weeks after conception
6. Acute intake (1 Bq) 15 weeks after conception
7. Acute intake (1 Bq) 25 weeks after conception
8. Acute intake (1 Bq) 35 weeks after conception
9. Constant chronic intake (1 Bq total) from 5 years before until conception
10. Constant chronic intake (1 Bq total) from 1 year before until conception
11. Constant chronic intake (1 Bq total) from conception to birth.

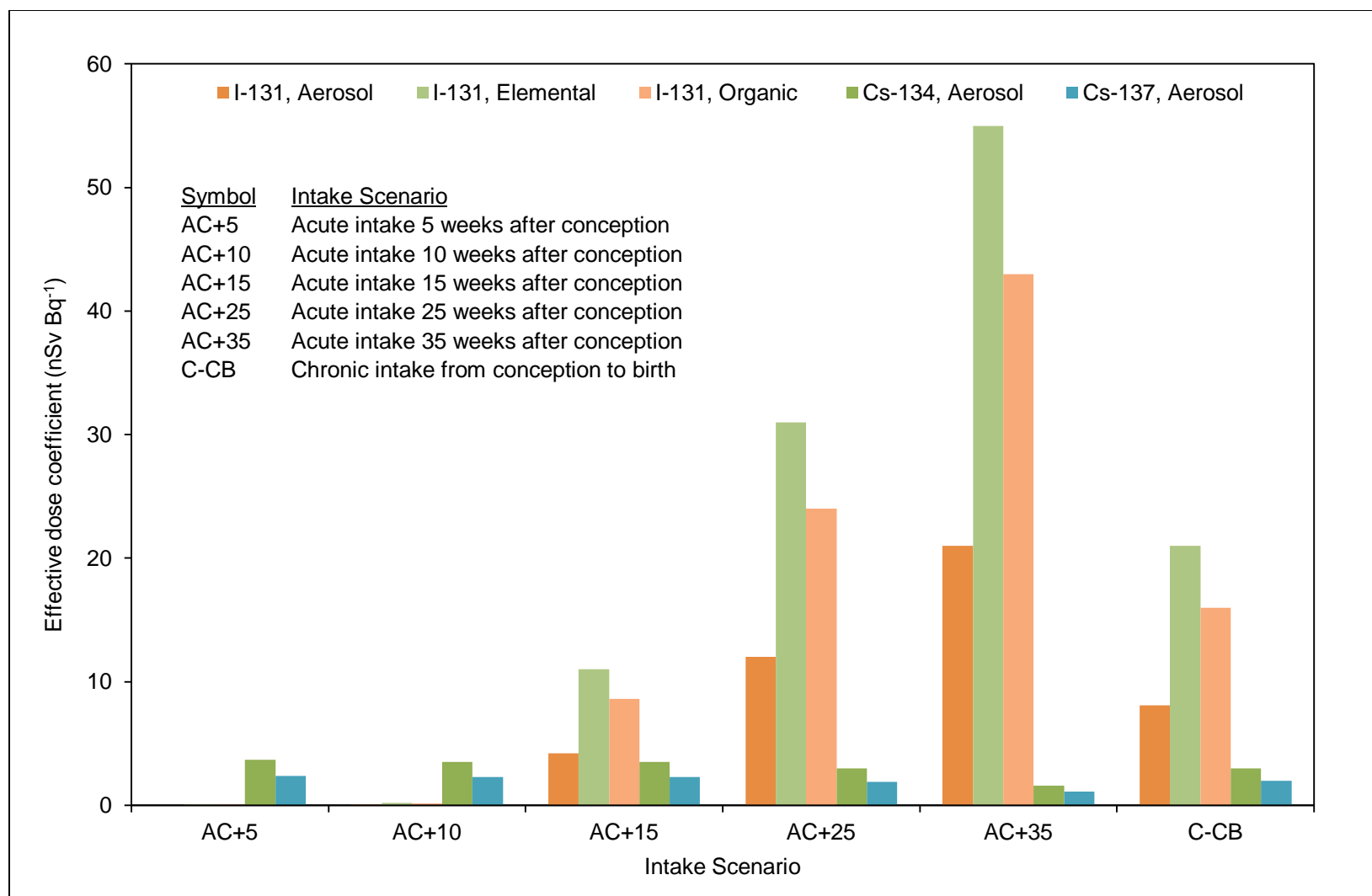
These 11 intake scenarios are examined in the next two sections to determine the scenario or scenarios that would produce the largest doses.

### **3.5.2. Dose Coefficients for Inhalation and Ingestion**

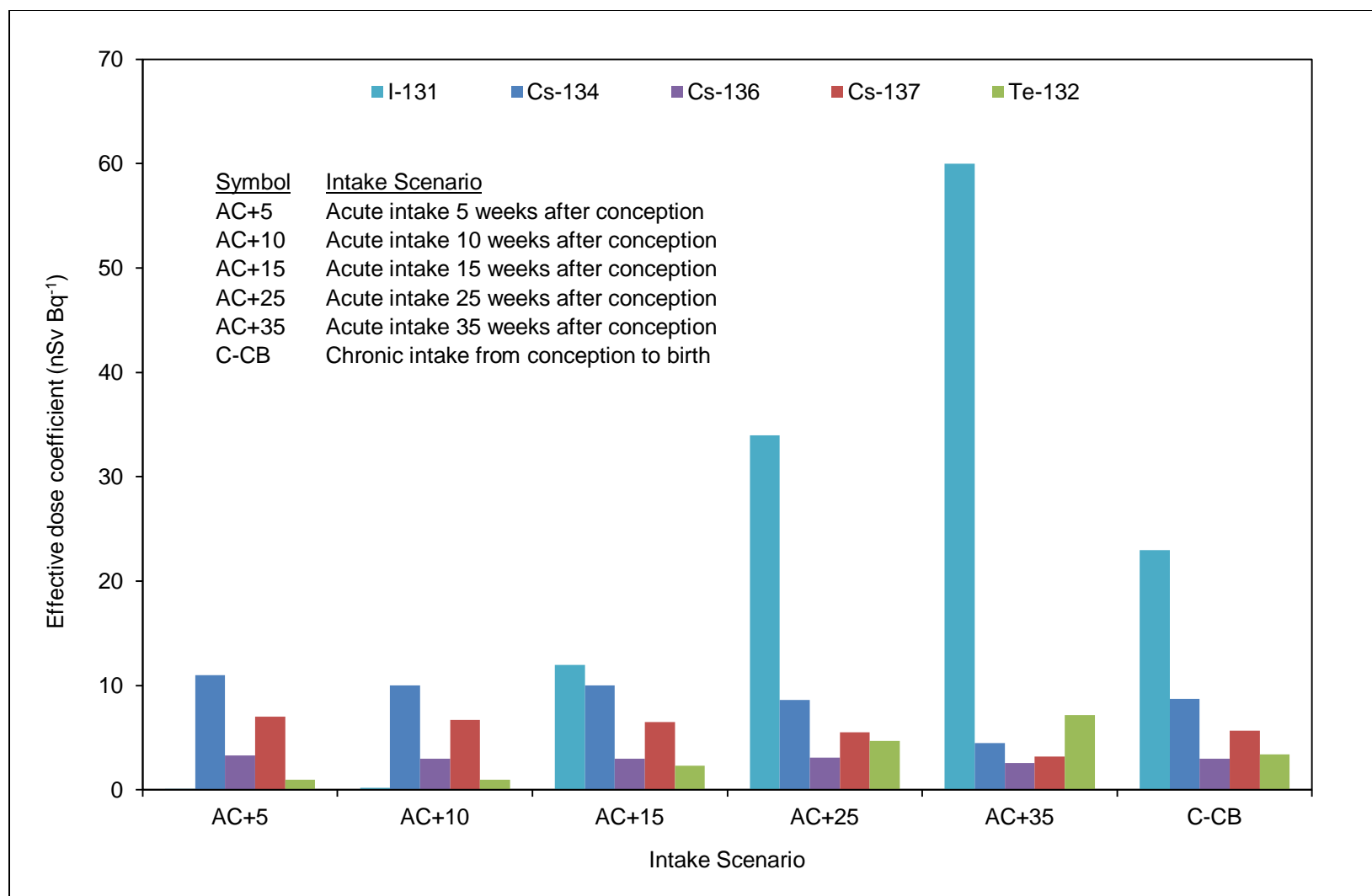
As discussed in this section, six of the eleven intake scenarios listed above have been determined to be the most likely to result in the highest embryo/fetus doses. Figure 2 and Figure 3 show the embryo/fetus DCs for effective dose as a function of these six intake scenarios for the radionuclides that contribute the most to the radiation doses: I-131, Cs-134, and Cs-137. For some of the following discussion, refer also to the bar chart of all the radionuclides listed in Table 1 (except<sup>13</sup> for Te-129, La-140, and Rb-86) shown in Appendix E, Section E-2. Most DCs are largest for acute intakes occurring at about 35 weeks after conception (AC+35), except for the cesium isotopes whose maxima occur for acute intakes occurring at conception (AC); this is seen best in Figure 3. Also, the DC for Sr-89 reaches a maximum for an acute intake 25 weeks after conception (AC+25). It is expected that organ DCs (the thyroid in particular) will follow the same pattern. In Figure 2 and Figure 3, the radionuclides in the legend should be read left to right to correspond to the bars representing the DCs.

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<sup>13</sup> These radionuclides were not included because DCs were only available for the AC+35 intake scenario. These radionuclides were included in the dose calculations.



**Figure 2. Embryo/fetus effective dose coefficients from inhalation by the mother**



**Figure 3. Offspring effective dose coefficients from ingestion by the mother**

The patterns seen in the figures can be explained by the radiological half-lives of the radionuclides, the behavior of the radionuclides in the body of both the mother and developing embryo/fetus, and the development of the embryo and fetus. Radionuclides that tend to distribute uniformly throughout the body (e.g., Cs-137) tend to have DCs that have their maximum values for intakes near the time of conception before the formation of the organs. This is seen most clearly in Figure 3. Those radionuclides that concentrate in organs (e.g., I-131) tend to have maximum values for DCs corresponding to intakes occurring later in gestation. Early in gestation (before organogenesis) there are no organs in which the radionuclides will concentrate.

### 3.5.3. Discussion of Intake Scenarios of the Embryo/Fetus

The calculated internal dose to the embryo/fetus depends on (1) the mother's intake rates of contaminated air, water, and soil (assumed to be set to the values presented in Section 2.2.4), (2) the concentrations (both absolute and relative) of radionuclides in the environmental media, and (3) the values of the DCs used. The radionuclide concentrations and DCs are functions of time; that is, the concentrations vary with time and the values of the DC depend on the stage of pregnancy at which an intake occurs. The greatest doses will occur when the absolute radionuclide concentrations are the highest and when the DCs maximize the dose for the environmental radionuclide concentrations, in particular the airborne radionuclide concentrations.

For all radionuclides considered here, there is an acute intake scenario DC that is greater than the DC for any chronic intake scenario. This is because for a chronic scenario the intake is either before conception or spread throughout the pregnancy (C-CB) so that there will always be a portion of the intake occurring at a time when less than the maximum dose will be delivered to the embryo or fetus.

As seen in Figure 2, the DCs for iodine reach their maximum values for an acute intake 35 weeks after conception (this is also the case for isotopes of tellurium); the DCs for cesium reach their maximum values for an acute intake at conception. For intakes at 35 weeks after conception, the DCs for the cesium isotopes are about one-half of their maximum values. Given the nature of the releases during the FDNPS accident and the limited exposure duration (two months) considered in this report, it is not possible to have been exposed to the same concentrations of radioactive material (and hence have the same acute intake) both at conception and 35 weeks after conception.

For equal concentrations of Cs-134 and Cs-137 (which are representative of the radiological conditions during OT (Cassata et al., 2012), the average inhalation DC for cesium reaches its maximum value of about  $3.2 \text{ nSv Bq}^{-1}$  at conception decreasing to about  $1.3 \text{ nSv Bq}^{-1}$  at 35 weeks after conception. The average<sup>14</sup> inhalation DC for I-131 increases from about  $0.05 \text{ nSv Bq}^{-1}$  at conception to its maximum value of about  $40 \text{ nSv Bq}^{-1}$  at 35 weeks after conception. A similar pattern is seen for ingestion intakes (Figure 3). The highest concentrations (airborne and waterborne) of radionuclides, particularly radioisotopes of iodine, cesium, and tellurium, occurred early during the two-month period. During the early phase of the accident, iodine airborne and waterborne concentrations were larger than cesium concentrations (Cassata

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<sup>14</sup> This inhalation DC was calculated as a weighted average of the following proportions of the forms of I-131: 28.5 percent aerosol (type F,  $1 \mu\text{m}$  activity median aerodynamic median diameter [AMAD]), 23.8 percent gaseous elemental, and 47.7 percent gaseous organic.

et al., 2012). Estimates of total releases indicated that the total amount of I-131 released was about five times the total combined amounts of Cs-134 and Cs-137 released (Sugiyama et al., 2012). Therefore, the largest potential intakes of radionuclides occurred during the period where the I-131 concentrations exceeded the total combined Cs-134 and Cs-137 concentrations. Table 2 shows Yokota AB data for early and later days during OT, and Table 3 shows representative examples of the DCs for I-131 and Cs-134+Cs-137.

**Table 2. Example Yokota AB airborne activity concentrations**

Activity Concentration (Bq m <sup>-3</sup> )			
I-131		Cs-134+Cs-137	
Mar 14–15	Apr 18–19	Mar 14–15	Apr 18–19
19	0.00705	13	0.0183

**Table 3. Example I-131 and total cesium inhalation effective dose coefficients**

Intake Scenario	Average I-131 DC (nSv Bq <sup>-1</sup> )	Average Cs DC (nSv Bq <sup>-1</sup> )
AC	0.05	3.2
AC+35	40	1.3

For the purposes of determining the dose maximizing intake scenario an inhalation rate of 30 m<sup>3</sup> d<sup>-1</sup> can be assumed. The calculated daily doses are shown below in Table 4.

**Table 4. Example daily effective doses**

Intake Scenario	Mar 14–15 (μSv)	Apr 18–19 (μSv)
AC	0.00128	1.77
AC+35	23.3	9.17

For this example of Yokota AB (Table 4), which is typical of conditions at the DARWG locations throughout OT, the dose from the AC+35 scenario is about four orders of magnitude greater than the dose received from the AC scenario if the exposure occurred soon after the accident started (March 14–15). However, by mid-April, the AC+35 dose decreases to about five times greater. At later dates, the ratio of the AC+35 dose to the AC dose decreases because of the radiological decay of I-131. For the AC scenario on March 14–15, I-131 accounts for about 2 percent of the total dose, whereas for the AC+35 scenario, I-131 accounts for about 98 percent of

the dose. On April 18–19 for the AC scenario, about 1 percent of the total dose is from I-131, whereas for the AC+35 scenario, I-131 accounts for about 92 percent of the dose.

Given that the largest intakes (highest concentrations in environmental media) occurred during a time when the iodine concentration exceeded the cesium concentration and the I-131 DC is a maximum value for exposures 35 weeks after conception, then, to ensure that the doses calculated in this report are likely to be greater than the actual dose received by any specific person, it is best to choose an intake scenario that maximizes the DCs for iodine. The intake scenario that best meets this condition is an acute intake 35 weeks after conception (AC+35). The DCs used for the embryo/fetus dose calculations are shown in Appendix E, Table E-1 and Table E-2. In practice, these DCs are applied to each day's intake over the entire two-month period, which is conservative because it assumes that each day's intake occurs at the time the DCs are at their greatest values.

### 3.6 Dose Results for the Embryo/Fetus

Table 5 presents the whole body effective and thyroid doses to the embryo/fetus under maximum exposure conditions for those locations where pregnant women might have been located. The doses were calculated using dose maximizing exposure conditions and a high-sided value for the adjustment factor in the DCs. The radiation doses include the contribution from external irradiation (assuming that the external radiation dose to the embryo/fetus equals the external radiation dose to the mother).

**Table 5. Embryo/fetus doses under maximum exposure conditions**

<b>DARWG Location (No.) *</b>	<b>Total Effective Dose<sup>†</sup> (mSv [rem])</b>	<b>Thyroid Dose<sup>†</sup> (mSv [rem])</b>
Misawa AB (D-1)	0.06 [0.006]	0.07 [0.007]
Yokota AB (D-8)	0.89 [0.089]	12 [1.2]
Akasaka Press Center (D-9)	0.80 [0.080]	12 [1.2]
Atsugi NAF (D-10)	0.68 [0.068]	10 [1.0]
Yokosuka NB (D-11)	0.63 [0.063]	10 [1.0]
Camp Fuji (D-12)	0.14 [0.014]	1.6 [0.16]
Iwakuni MCAS (D-13)	0.021 [0.0021]	0.23 [0.023]
Sasebo NB (D-14)	0.027 [0.0027]	0.30 [0.030]

\* Location D-5, J-Village is not included in this report because of the limited environmental data. A characterization of the radiological environment of J-Village is included in McKenzie-Carter et al. (2013).

<sup>†</sup> These doses include contributions from mother's radionuclide intakes as described in Section 2.2.4 and external radiation exposure under maximum exposure conditions. Also, an UF of 3 was applied to the DCs of Cs, I, and Te used to calculate the internal radiation dose.

All radiation exposure scenarios include the possibility that a woman might have been pregnant and present at any of the locations before she became aware of the pregnancy and she remained at the location for two months. Given the high values used for mothers' intake rates, no accounting for time spent indoors, use of the maximizing DC, and the adjustment factor of three, the DARWG believes that the doses presented in Table 5 are very conservative in that an individual's actual doses are very likely to be less than those presented here. These doses are

compared to the distribution of doses developed during a preliminary probabilistic analysis in Section 6.3.

Table 6 shows the ranges of embryonic/fetal doses under a variety of intake rates and values of time spent indoors. The range of parameter values used to calculate the doses in Table 6 are shown in Appendix C.

**Table 6. Ranges of doses for the embryo/fetus for a variety of exposure conditions**

<b>DARWG Location (No.) *</b>	<b>Total Effective Dose<sup>†</sup> (mSv [rem])</b>	<b>Thyroid Dose<sup>†</sup> (mSv [rem])</b>
Misawa AB (D-1)	0.033–0.060 [0.0033–0.0060]	0.037–0.07 [0.0037–0.007]
Yokota AB (D-8)	0.40–0.89 [0.040–0.089]	5.0–12 [0.50–1.2]
Akasaka Press Center (D-9)	0.35–0.80 [0.035–0.080]	5.0–12 [0.50–1.2]
Atsugi NAF (D-10)	0.32–0.68 [0.032–0.068]	4.4–10 [0.44–1.0]
Yokosuka NB (D-11)	0.29–0.63 [0.029–0.063]	4.4–10 [0.44–1.0]
Camp Fuji (D-12)	0.070–0.14 [0.0070–0.014]	0.73–1.6 [0.073–0.16]
Iwakuni MCAS (D-13)	0.010–0.021 [0.0010–0.0021]	0.11–0.23 [0.011–0.023]
Sasebo NB (D-14)	0.013–0.027 [0.0013–0.0027]	0.14–0.30 [0.014–0.030]

\* Location D-5, J-Village is not included in this report because of the limited environmental data. A characterization of the radiological environment of J-Village is included in McKenzie-Carter et al. (2013).

<sup>†</sup> These doses include contributions from mother's radionuclide intakes as described in Section 2.2.4, and external radiation exposure under a range of exposure conditions (See Appendix C.). Also, an UF of 3 was applied to the DCs of Cs, I, and Te used to calculate the internal radiation dose.



## **Section 4.**

### **Radiation Doses to a Nursing Infant**

#### **4.1 Potentially Exposed Population: Infants Aged Less than 12 Months**

To assess the dose to nursing infants, the DARWG examined the potential radiation exposure of infants who were less than 12 months old<sup>15</sup>. Although the purpose of this section is to discuss the methods used to estimate and report the radiation dose to nursing infants, it is necessary to evaluate the mother's intakes of radioactive material, and so, the mother's intakes of radioactive materials by ingestion and inhalation are also examined.

#### **4.2 Sources of Radiation Exposure**

The radiation dose to a nursing infant arises from the following sources: external radiation from the environment, ingestion of mother's milk containing radionuclides, intakes by the infant of air, water, and soil, and external radiation from radionuclides in the mother. External radiation exposure and the intakes by an infant other than mother's milk together are referred to as direct exposure in this report. This report presents the results of calculations to estimate conservative values of the radiation dose to a nursing infant from all sources of radiation exposure. The contribution to an infant's radiation dose from radionuclides in the mother is small and is discussed in Section 4.5. The radiation doses arising from an infant's exposure to radionuclides in the environment (excluding mother's milk) are presented in Cassata et al. (2012).

#### **4.3 Dose Coefficients for Nursing Infants from Radionuclides in Mother's Milk**

A detailed discussion of radiation doses to the nursing infant can be found in ICRP Publication 95 (ICRP, 2004), which states:

Relevant human and animal data on elemental and radionuclide transfer to milk are reviewed. The biokinetic models for adults given in earlier ICRP publications are adapted to include transfer to milk. Model predictions of fractional transfer of ingested or inhaled activity to milk are discussed in the report, and the corresponding dose coefficients for the infant are compared with dose coefficients for in utero exposure, as given in Publication 88 (ICRP, 2001a). Illustrative information is also given on doses to the female breast from radionuclides in breast milk, and external doses received by the child from radionuclides retained in the tissues of the mother.

The DCs used in calculations of committed effective dose and committed equivalent dose in this report were taken from the ICRP CD-ROM 3 database of DCs (ICRP, 2007b) containing committed effective doses per unit intake (DCs) and committed equivalent doses per unit intake (DCs) to various tissues. In this database, the intake occurs in the mother, while the dose is calculated to the infant. Results are given for both workers and members of the public. Results

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<sup>15</sup> This age was chosen for a U.S. population based on information in chapter 15 of EPA (2011).

are consistent with the latest ICRP advice given in Publication 95. The database extends the results given in the Publication to include DCs for ten aerosol sizes and for five integration periods after intake. The intake scenarios and radionuclide parameters in the ICRP (2007b) database are:

- Thirty-five (35) elements
- Members of the public and workers
- Inhalation of aerosols and vapors
- Ingestion
- Ten aerosol sizes
- Thirty-two organ doses, remainder organ doses, and effective doses
- Fourteen acute intake scenarios
- Four chronic intake scenarios.

In developing the DCs for a nursing infant, the ICRP (2004): (1) considered acute and chronic ingestion and inhalation intakes before and during pregnancy and also during lactation; (2) extended their adult biokinetic models to include the transfer to mother's milk; (3) used the DCs for the three month old infant for the entire nursing period; and, (4) assumed six months of breastfeeding starting at zero (intake of mother's milk) and increasing linearly to  $0.8 \text{ L d}^{-1}$  during the first week.

The following radionuclides are not included in the ICRP databases of DCs for the nursing infant: I-130, La-140, Rb-86, and Te-129. No explanation was found for the exclusion of these radionuclides from the ICRP database. However, Mr. Timothy Fell and Mrs. Tracy Smith, of the U.K. Health Protection Agency provided I-130 and Te-129 DCs for both effective and thyroid doses (Fell, 2012; Smith, 2013).

#### **4.3.1. Mother's Milk and Total Fluid Intake**

The EPA (2011) estimates that the mean amount of mother's milk intake for a nursing infant over the first year after birth ranges from about  $0.5$  to  $0.8 \text{ L d}^{-1}$  with an upper percentile<sup>16</sup> value of about  $1 \text{ L d}^{-1}$  for all age groups up to age one year. For its development of DCs for nursing infants, the ICRP (2004) "assumed that consumption increases linearly over the first week of life to  $800 \text{ ml/day}$  and continues at this rate for 6 months (26 weeks);" there is no accounting for reduced consumption during weaning. The ICRP DCs, despite being based on a six-month duration of breastfeeding, can be used for estimating the doses from longer or shorter periods of breastfeeding by artificially choosing an effective intake time before or after the actual intake time (ICRP, 2004). However, because the total amount of activity actually transferred to the infant is not sensitive to when the mother's intake occurred (because either the radionuclides are quickly transferred to mother's milk or the radionuclides have short radiological half-lives

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<sup>16</sup> According to the EPA (2011) for the recommended values of mother's milk intake, "the upper percentile is reported as mean plus 2 standard deviations." In general, the term "upper percentile" is "intended to represent values in the upper tail (i.e., between the 90<sup>th</sup> and 99.9<sup>th</sup> percentile) of the distribution of values for a particular exposure factor" (EPA, 2011).

and transform before being transferred) adjustments are not usually needed (ICRP, 2004). In actuality, the most significant intakes during OT would have occurred during the first several weeks of the accident. Therefore, no adjustments are made to the ICRP DCs for use in this report to account for differences in the duration of breastfeeding.

In Cassata et al. (2012), the DARWG adopted the 95<sup>th</sup> percentile value of the consumers-only<sup>17</sup> water intake for a three to six month old infant ( $1.2 \text{ L d}^{-1}$ ). As noted in the previous paragraph, the ICRP assumed a daily intake rate of  $0.8 \text{ L d}^{-1}$  leaving a difference in the assumed total water intake of  $0.4 \text{ L d}^{-1}$ . To calculate the total radiation dose to nursing infants under dose maximizing assumptions, it was assumed in this report that an infant ingests  $0.8 \text{ L d}^{-1}$  of mother's milk and  $0.4 \text{ L d}^{-1}$  of water from other sources for a fixed, total fluid intake of  $1.2 \text{ L d}^{-1}$ , which is the total fluid intake used in Cassata et al. (2012) for the 0 to 1 year age group.

#### **4.3.2. Formula-fed Infants**

The water ingestion rate used in Cassata et al. (2012) for a three to six month old infant was  $1.2 \text{ L d}^{-1}$  including water added in the preparation of food and beverages<sup>18</sup>. According to Kahn and Stralka (2009)<sup>19</sup> from which the EPA recommendations were drawn (and hence those in Cassata et al. [2012]), the consumers-only water intake rates for infants “are considered more representative of the water intake by infants fed with formula either diluted from powdered or concentrated mixture.” Furthermore, most of the water intake by infants is indirect; that is, from infant formula or reconstituted juice (Kahn and Stralka, 2009). The DARWG has not considered the use of bottled water for infant formula. This is conservative because a population concerned about radionuclides in water is more likely to use bottled water, which would be free of radionuclides from FDNPS. Therefore, the water ingestion rate for infants used in Cassata et al. (2012) is sufficient to account for water used in infant formula preparation.

### **4.4 Intake Scenarios for Nursing Infants**

#### **4.4.1. ICRP Intake Scenarios for Nursing Infants**

For this analysis of the radiation doses to the nursing infant resulting from intakes during Operation Tomodachi, the radionuclides of concern (Section 2.1), their physical and chemical properties (Section 2.2.1), and intake rates (Section 2.2.4) have been specified. Some flexibility is introduced by the ability to choose from 18 intake scenarios (14 acute and four chronic) presented in the ICRP CD-ROM 3 (ICRP, 2007b):

1. Acute intake (1 Bq) 2.5 years prior to conception
2. Acute intake (1 Bq) 6 months prior to conception
3. Acute intake (1 Bq) at conception

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<sup>17</sup> According to the EPA (2011), “Consumer-only intake represents the quantity of water consumed only by individuals that reported consuming water during the survey period.”

<sup>18</sup> The reported ingestion rates are for “combined direct and indirect water from community water supply” (EPA, 2011). Direct water is water ingested as a beverage; indirect water is water added in the preparation of food or beverages (EPA, 2011). A community water supply is tap water obtained from a community or municipal water supply (EPA, 2011).

<sup>19</sup> This journal article is cited in EPA (2011) as being published in 2008 and is cited therein as “Kahn (2008).”

4. Acute intake (1 Bq) 5 weeks after conception
5. Acute intake (1 Bq) 10 weeks after conception
6. Acute intake (1 Bq) 15 weeks after conception
7. Acute intake (1 Bq) 25 weeks after conception
8. Acute intake (1 Bq) 35 weeks after conception
9. Acute intake (1 Bq) at birth
10. Acute intake (1 Bq) 1 week after birth
11. Acute intake (1 Bq) 5 weeks after birth
12. Acute intake (1 Bq) 10 weeks after birth
13. Acute intake (1 Bq) 15 weeks after birth
14. Acute intake (1 Bq) 20 weeks after birth
15. Constant chronic intake (1 Bq total) from 5 years before until conception
16. Constant chronic intake (1 Bq total) from 1 year before until conception
17. Constant chronic intake (1 Bq total) from conception to birth
18. Constant chronic intake (1 Bq total) from birth for 6 months.

The radiation dose to a nursing infant from intakes of radionuclides by the mother will be dominated by the contributions of the radionuclides of iodine, cesium, and tellurium, which have relatively short half-lives (iodine and tellurium), are not avidly retained by the body (iodine and cesium), and are not efficiently transferred to mother's milk (Te) (ICRP, 2004). For example, the range of times to maximum I-131 content in mother's milk was 1.9 to 52 hours (Simon et al., 2002), 90 percent of Cs is retained by the lactating female with a half-time of about 75 days (ICRP, 2004), and about 1 percent of absorbed tellurium is transferred to mother's milk following an acute intake by the mother one week after birth (ICRP, 2004). Therefore intakes before birth (items 1 through 8, 15, 16, and 17 above) will be unimportant compared to intakes at or after birth (items 9 through 14 and 18 above). These seven intake scenarios are examined in the next section to determine the scenario or scenarios that apply best to this report.

#### **4.4.2. Discussion of Intake Scenarios for a Nursing Infant**

Figure 4 and Figure 5 show the nursing infant DCs for effective dose as a function of intake scenario for the radionuclides that contribute the most to the radiation doses: I-131, Cs-134, and Cs-137. A bar chart of DCs for all the radionuclides listed in Table 1, except for La-140, and Rb-86<sup>20</sup>, is included in Appendix E, Section E-2. The radioisotopes of iodine, I-131 in particular, dominate the effective dose per unit intake by the mother. The DC for Sr-90 is larger than the DCs for the cesium and tellurium isotopes, but its contribution to the overall dose is small because its concentration in environmental media is very small. The DCs are largest and

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<sup>20</sup> The DCs for La-140, and Rb-86 were not available at the time of this report, but the contribution from these radionuclides is expected to be small. Mr. Tim Fell of the U.K. Health Protection Agency indicated that to derive DCs would require resources that were unavailable (Fell, 2013) at the time of this report.

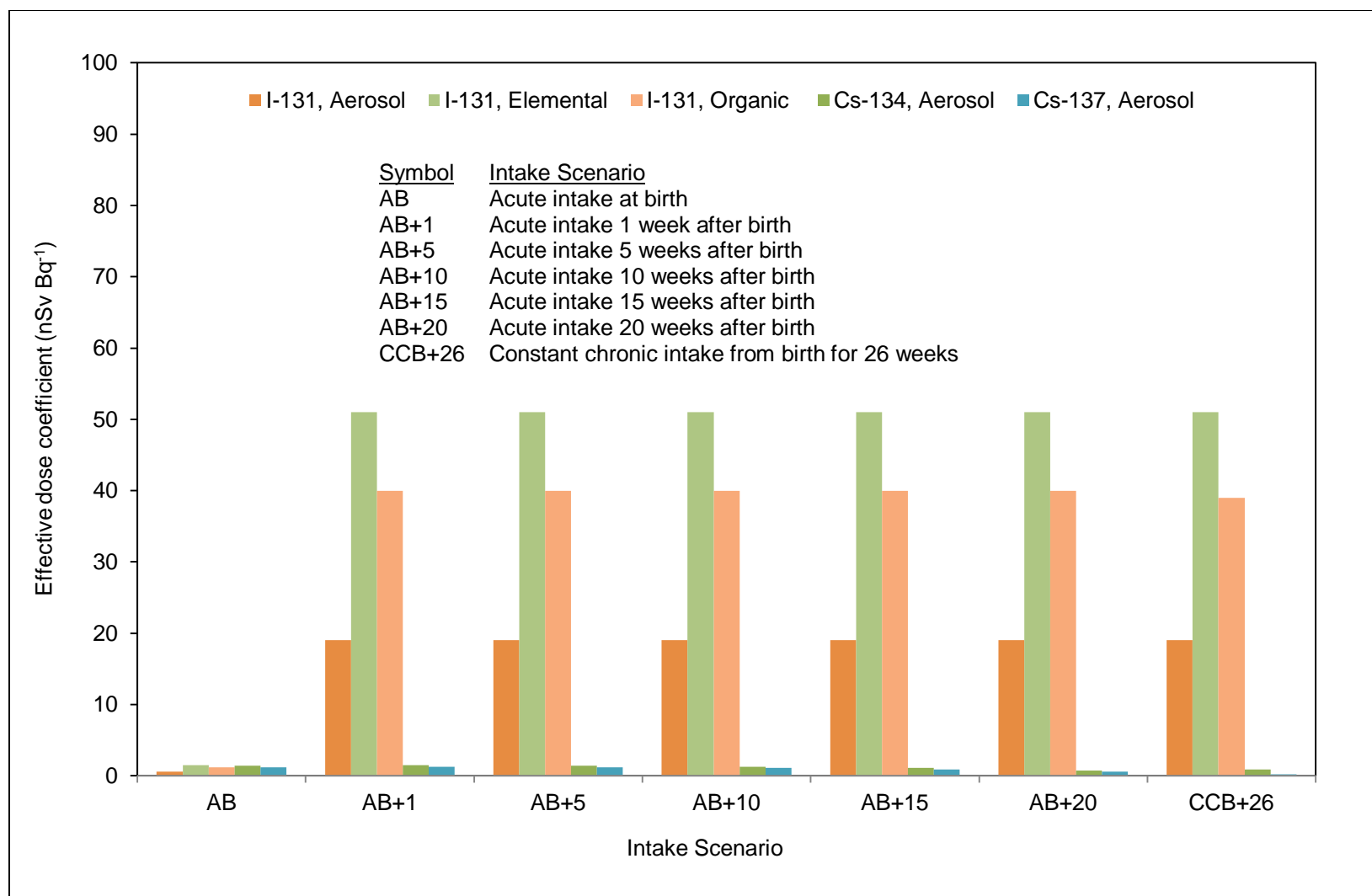
constant for acute intakes occurring after birth and begin to decline at about 20 weeks after birth. The DCs for a constant chronic intake from birth to 26 weeks after birth are smaller than those for the acute intakes. It is expected that organ DCs (the thyroid in particular) will follow the same pattern. As discussed in Section 3.5.3, to ensure that the doses calculated in this report are likely to be greater than the true dose received by any specific person, it is best to choose an intake scenario that maximizes the DCs for iodine<sup>21</sup>. For the nursing infant dose calculations, the DCs for an acute intake one week after birth (AB+1) were used. The DCs used for the nursing infant dose calculations are shown in Appendix E, in Table E-1 and Table E-2 in Section E-2. The DCs for Cs-134, Cs-137, and I-131, the most important contributors to the radiation dose, are shown in Figure 4.

#### **4.5 External Radiation Dose to the Infant from Radionuclides in the Mother**

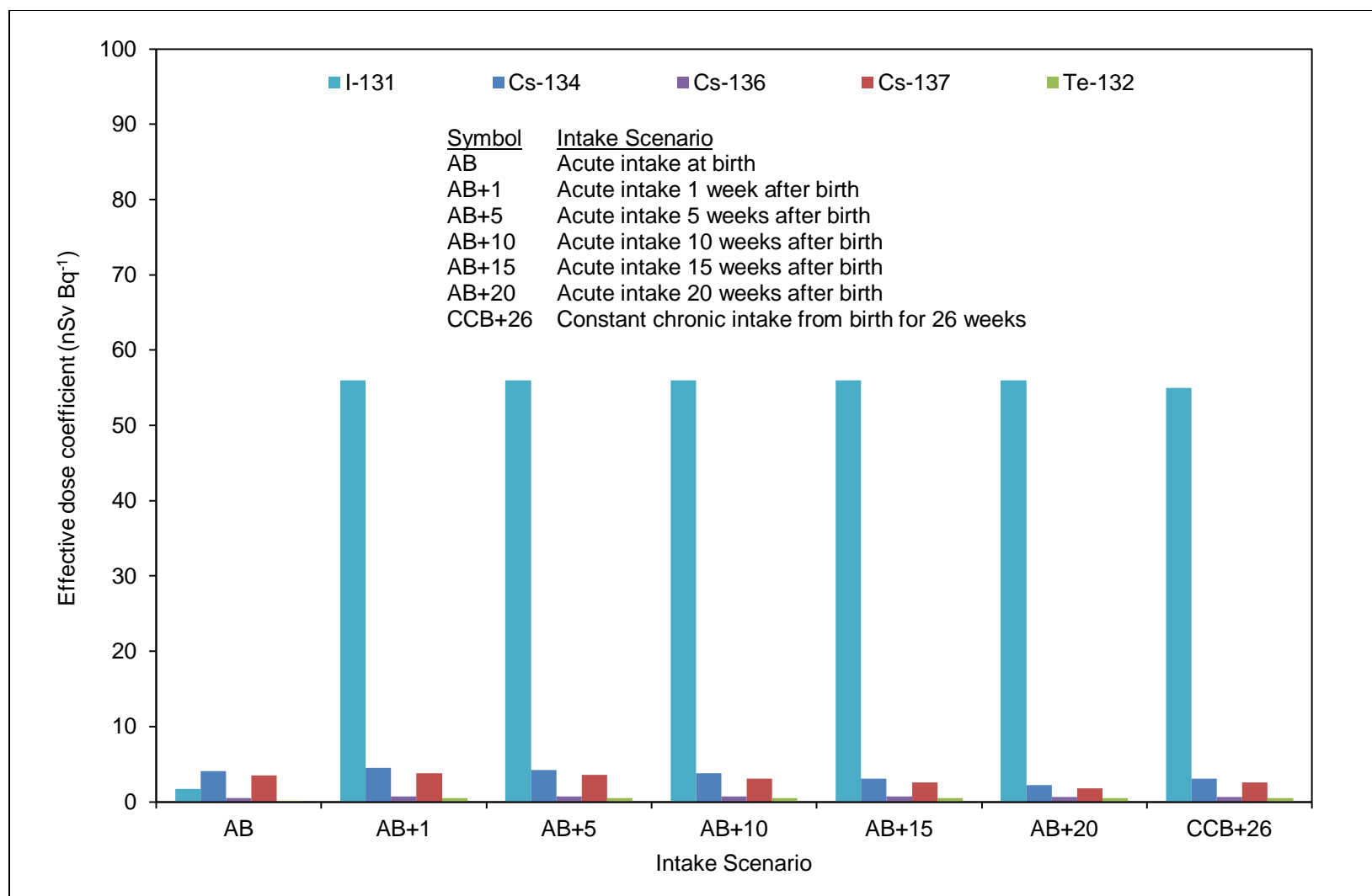
Photon-emitting radionuclides deposited in the mother's body can irradiate a nursing infant held by the mother. Because the source of radiation exposure is outside the infant, this is an external radiation dose. ICRP Publication 95 (ICRP, 2004) examined this issue and provided dose information for those radionuclides that emit substantial photon energy. For an acute intake by the mother 1 week after birth, the external dose to the nursing infant is about 0.03 percent of the internal dose for I-131 and the ratio is about 7 percent for Cs-137 (ICRP, 2004). To calculate these doses the ICRP (2004) assumed that the infant spent 2 h d<sup>-1</sup> breastfeeding, 1 h d<sup>-1</sup> being held in the mother's lap and 1 h d<sup>-1</sup> over the mother's shoulder. Therefore, the external radiation dose to a nursing infant from radionuclides of concern (Section 2.2.1) in the mother's body is likely a small contribution compared to the internal radiation dose from ingesting mother's milk and the infant's radiation dose from environmental internal and external exposures, and can be ignored.

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<sup>21</sup> The acute ingestion and inhalation intake DCs for I and Te reach a maximum value at 1 week after birth and remain constant for acute intake to 20 weeks after birth; for Cs the DCs peak 1 week after birth and slowly decline thereafter.



**Figure 4. Nursing infant effective dose coefficients for inhalation by the mother**



**Figure 5. Nursing infant effective dose coefficients for ingestion by the mother**

#### 4.6 Dose Results for Nursing Infants

Table 7 presents the whole body effective and thyroid doses to a nursing infant calculated from both the mother's and infant's exposure using dose maximizing conditions (excluding HADR efforts) and a high-sided value for the DCs. The radiation doses include the contribution from all sources of the infant's radiation exposure. The external radiation dose to the nursing infant is discussed in Section 4.5 and was found to be small compared to the other sources of radiation exposure.

**Table 7. Doses to the nursing infant under maximum exposure conditions**

<b>DARWG Location (No.) *</b>	<b>Total Effective Dose<sup>†</sup> (mSv [rem])</b>	<b>Thyroid Dose<sup>†</sup> (mSv [rem])</b>
Misawa AB (D-1)	0.07 [0.007] <sup>§</sup>	0.16 [0.016] <sup>§</sup>
Yokota AB (D-8)	1.3 [0.13]	21 [2.1]
Akasaka Press Center (D-9)	1.2 [0.12]	21 [2.1]
Atsugi NAF (D-10)	1.1 [0.11]	18 [1.8]
Yokosuka NB (D-11)	1.0 [0.10]	18 [1.8]
Camp Fuji (D-12)	0.37 [0.037]	6.1 [0.61]
Iwakuni MCAS (D-13)	0.05 [0.005]	0.89 [0.089]
Sasebo NB (D-14)	0.07 [0.007]	1.1 [0.11]

\* Location D-5, J-Village is not included in this report because of the limited environmental data. A characterization of the radiological environment of J-Village is included in McKenzie-Carter et al. (2013).

<sup>†</sup> These doses include contributions from mother's radionuclide intakes as described in Section 2.2.4, the infant's intake of air, soil, 0.4 L d<sup>-1</sup> of water and 0.8 L d<sup>-1</sup> of mother's milk. (See Section 4.3.1.), and external radiation exposure under maximum exposure conditions. Also, an adjustment factor of 3 was applied to the DCs of Cs, I, and Te used to calculate the internal radiation dose.

<sup>§</sup> The ratio of the effective dose to the thyroid dose at Misawa AB is about 2.3 compared to a ratio of about 15 for the other locations. The difference is because at Misawa AB the external radiation dose is the dominant component of the total radiation dose. In the other locations, the internal radiation dose is equal to or larger than the external radiation dose.

Doses for all eight selected DARWG locations are estimated or determined based on the possibility that a nursing mother might have been present at any of the locations for any amount of time and then returned to nurse an infant at a different location. Given the values used for mother's intake rates, no accounting for time spent indoors, and the adjustment factor of three, the DARWG believes that the doses presented in Table 7 are very conservative in that nursing infants' actual doses are very likely to be less than those presented here.

The radiation doses to a nursing infant as discussed in this section include contributions from direct exposure (external radiation and the infant's intakes of air, water, and soil) and consumption of mother's milk. The external radiation dose from radionuclides in the mother is small compared to the other sources and is considered to be subsumed in these high-sided dose calculations. The radiation doses (under dose maximizing conditions) from milk consumption and the infant's direct exposure are shown in Table 8.



**Table 8. Infant's doses from mother's milk consumption and direct exposure**

<b>DARWG Location (No.) *</b>	<b>Milk Consumption</b>				<b>Direct Exposure</b>			
	<b>TED* (mSv [rem])</b>		<b>Thyroid Dose<sup>†</sup> (mSv [rem])</b>		<b>TED<sup>†</sup> (mSv [rem])</b>		<b>Thyroid Dose<sup>†</sup> (mSv [rem])</b>	
Misawa AB (D-1)	0.0	[0.0]	0.01	[0.001]	0.07	[0.007]	0.15	[0.015]
Yokota AB (D-8)	0.5	[0.05]	11.0	[1.1]	0.8	[0.08]	10.0	[1.0]
Akasaka Press Center (D-9)	0.5	[0.05]	11.0	[1.1]	0.7	[0.07]	10.0	[1.0]
Atsugi NAF (D-10)	0.4	[0.04]	9.0	[0.9]	0.7	[0.07]	9.0	[0.9]
Yokosuka NB (D-11)	0.4	[0.04]	9.0	[0.9]	0.6	[0.06]	9.0	[0.9]
Camp Fuji (D-12)	0.1	[0.01]	2.0	[0.2]	0.3	[0.03]	5.0	[0.5]
Iwakuni MCAS (D-13)	0.01	[0.001]	0.2	[0.02]	0.04	[0.004]	0.7	[0.07]
Sasebo NB (D-14)	0.02	[0.002]	0.3	[0.03]	0.05	[0.005]	0.9	[0.09]

\* Location D-5, J-Village is not included in this report because of the limited environmental data. A characterization of the radiological environment of J-Village is included in McKenzie-Carter et al. (2013).

<sup>†</sup> The values in this table are rounded for illustration and do not necessarily sum to the values in Table 7.

For Misawa (D-1), Camp Fuji (D-12), Iwakuni MCAS (D-13), and Sasebo (D-14), environmental data for many days are missing, and so internal radiation doses were inferred from external radiation doses as discussed in Cassata et al. (2012). At these locations, the internal radiation doses for nursing infants might likely have been at background levels or slightly greater. At the remaining locations, where more robust environmental data were available, the radiation dose (internal) from mother's milk consumption is about 40–50 percent of the total effective dose and about 35–50 percent of the thyroid dose. The rough equivalency of the internal dose contributions from milk consumption and direct exposure arises from (1) the fact that the internal radiation dose is proportional to the product of the DC and the intake rate (or total intake) for the same concentration in any given medium (e.g., air) and (2) intakes of I-131 by inhalation of air were greater than intakes by ingestion of water and mother's milk during OT<sup>22</sup>. An example of the contribution to dose for the inhalation of elemental I-131 vapor is shown in Table 9 where it is assumed that the mother and infant are exposed to the same radiological conditions.

<sup>22</sup> This second condition, although true for many of the exposures during most of OT, is not universally true. That is, not all exposures involve airborne concentrations, inhalation intakes, and subsequent doses greater than those from other routes of exposure.

**Table 9. Example contributions to dose from inhaled I-131 in mother's milk and direct inhalation by an infant**

<b>Effective Dose</b>			
	<b>DC (nSv Bq<sup>-1</sup>)</b>	<b>Intake Rate (m<sup>3</sup> d<sup>-1</sup>)</b>	<b>Dose Rate<sup>*</sup> (nSv d<sup>-1</sup>)</b>
Mother's Milk	51	30	1,530
Infant's Additional Intake <sup>†</sup>	170	9.2	1,600
<b>Thyroid Dose</b>			
Mother's Milk	1,000	30	30,000
Infant's Additional Intake <sup>†</sup>	3,300	9.2	30,300

<sup>\*</sup> This is based on an assumed airborne concentration of elemental I-131 vapor of 1 Bq m<sup>-3</sup>.

<sup>†</sup> Represents infant's inhalation of airborne I-131

In general, the dose to a nursing infant from mother's milk is about three times the dose from the direct exposure to the infant. An example for I-131 ingestion is shown in Table 10. As in Table 9 it is assumed that the mother and infant are exposed to the same radiological conditions. Here it is assumed that the infant ingests 0.8 L d<sup>-1</sup> of mother's milk and 0.4 L d<sup>-1</sup> of water for a total liquid intake of 1.2 L d<sup>-1</sup> as used in Cassata et al. (2012).

**Table 10. Example contributions to dose from ingested I-131 in mother's milk and direct ingestion by an infant**

<b>Effective Dose</b>			
	<b>DC (nSv Bq<sup>-1</sup>)</b>	<b>Intake Rate (L d<sup>-1</sup>)</b>	<b>Dose Rate<sup>*</sup> (nSv d<sup>-1</sup>)</b>
Mother's Milk	50	4	200
Infant's Additional Intake <sup>†</sup>	180	0.4	70
<b>Thyroid Dose</b>			
Mother's Milk	1,200	4	4,800
Infant's Additional Intake <sup>†</sup>	3,700	0.4	1,500

<sup>\*</sup> This is based on an assumed concentration of I-131 in water of 1 Bq L<sup>-1</sup>.

<sup>†</sup> Represents infant's ingestion of I-131 in formula, water, and other liquids.

For comparison additional calculations were performed where the time spent indoors, the mothers' breathing rates, and the mothers' water ingestion rates were allowed to vary as shown in Appendix C. The DCs and DC UF were kept the same as for the dose maximizing results shown in Table 7; that is, DCs for an acute intake one week after birth (AB+1) and a UF of 3 were used. The infant's total fluid intake was held constant at 1.2 L d<sup>-1</sup> (a rate of 0.8 L d<sup>-1</sup> for mother's milk and 0.4 L d<sup>-1</sup> for water), but the other exposure parameter values for the infant were varied as shown in Appendix C. Table 11 shows the ranges of nursing infant doses under a variety of exposure conditions.

**Table 11. Ranges of doses to the nursing infant**

<b>DARWG Location (No.) *</b>	<b>Total Effective Dose<sup>†</sup> (mSv [rem])</b>	<b>Thyroid Dose<sup>†</sup> (mSv [rem])</b>
Misawa AB (D-1)	0.03–0.07 [0.003–0.007]	0.04–0.16 [0.004–0.016]
Yokota AB (D-8)	0.58–1.3 [0.058–0.13]	8.9–21 [0.89–2.1]
Akasaka Press Center (D-9)	0.54–1.2 [0.054–0.12]	8.9–21 [0.89–2.1]
Atsugi NAF (D-10)	0.48–1.1 [0.048–0.11]	7.7–18 [0.77–1.8]
Yokosuka NB (D-11)	0.45–1.0 [0.045–0.10]	7.7–18 [0.77–1.8]
Camp Fuji (D-12)	0.15–0.37 [0.015–0.037]	2.5–6.1 [0.25–0.61]
Iwakuni MCAS (D-13)	0.02–0.05 [0.002–0.005]	0.36–0.89 [0.036–0.089]
Sasebo NB (D-14)	0.03–0.07 [0.003–0.007]	0.46–1.1 [0.046–0.11]

\* Location D-5, J-Village is not included in this report because of the limited environmental data. A characterization of the radiological environment of J-Village is included in McKenzie-Carter et al. (2013).

<sup>†</sup> These doses include contributions from mother's radionuclide intakes as described in Section 2.2.4, the infant's intake of air, soil, 0.4 L d<sup>-1</sup> of water and 0.8 L d<sup>-1</sup> of mother's milk. (See Section 4.3.1.), and external radiation exposure under a range of exposure conditions (See Appendix C.). Also, an adjustment factor of 3 was applied to the DCs of Cs, I, and Te used to calculate the internal radiation dose

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## **Section 5.**

### **Probabilistic and Uncertainty Analysis**

#### **5.1 Probabilistic Assessment of Doses and Uncertainty**

A probabilistic analysis of the embryo/fetus doses for exposure at Yokota AB was performed to provide a basis for comparison with the doses estimated by deterministic methods and reported in Section 3. This analysis helps to assess whether the doses reported in Section 3 are sufficiently conservative, i.e., high sided and meet the goal of being at or above the 95-percent confidence level determined in the probabilistic analysis. To create reliable dose distributions, realistic central estimates and uncertainty distributions were used to model the various dose input parameters.

The distributions of most dose input parameters were previously developed in Chehata et al. (2013). In particular, the environmental data and corresponding uncertainty distributions are independent of the exposed person or cohort and are used without any changes. However, life style and physiological dose parameters depend on the exposed individual and were therefore developed for this probabilistic analysis using values specific to the pregnant woman and to the embryo/fetus. Nevertheless, pregnant women are assumed to be in the adults' category ( $> 17$  years), and to have similar life styles as other adults at Yokota AB and the same distribution of time spent indoors versus outdoors. It is also assumed that protection factors afforded while the pregnant woman is inside buildings are the same as in Chehata et al. (2013). Also, all correlations and dependencies among the dose model parameters are kept the same.

Chehata et al. (2013) describes the probabilistic analyses developed to estimate distributions of total effective doses and total equivalent doses to the thyroid from ionizing radiation for DOD-affiliated individuals who were in Japan following the nuclear accident at the FDNPS during the two-month period from March 12, 2011, to May 11, 2011. These analyses were performed to assess whether the doses estimated by the methods reported in Cassata et al. (2012) were sufficiently conservative (high sided) and met the goal of being at or above the 95-percent confidence level. The report included probabilistic dose assessments for adults and 1-to-2 year-old children who were present at Yokota AB following the accident at the FDNPS.

#### **5.2 Scope of Uncertainty Analysis**

For this report, the probabilistic analysis was performed to assess the embryo/fetus doses for pregnant women who were principally located at Yokota AB during the two-month period following March 11, 2011. Yokota AB was selected because it is representative of locations with children and pregnant women. Also, the radiological data associated with Yokota AB are robust enough to support both deterministic and probabilistic estimates. A similar analysis has not been performed for a nursing infant of a lactating mother. The analysis and results included in this section support the decision that analyses for nursing infants and other locations are not needed because the doses estimated using deterministic methods for the case studied are shown to be conservatively high sided, and because of the similarity of these doses to the doses estimated for the unstudied locations. The decision to include one analysis in this report is also based on the

findings of the probabilistic analysis conducted for shore-based individuals (i.e., 1-to-2 year-old children and adults), which demonstrated that the doses estimated by deterministic methods (Cassata et al., 2012) were higher than the 99<sup>th</sup> percentile values of the probabilistic dose distributions (Chehata et al., 2013).

### **5.3 Distributions of Dose Parameters**

#### **5.3.1. Environmental Parameters**

Environmental monitoring data and related uncertainty distributions used for this probabilistic analysis are detailed in Chehata et al. (2013). Pregnant women are assumed to have been exposed to the same external and internal sources as other personnel who were at Yokota AB from during the two months covered by the OTR.

#### **5.3.2. Parameters for Mother's Exposure to Radiation**

##### **5.3.2.1 Time Spent Outdoors**

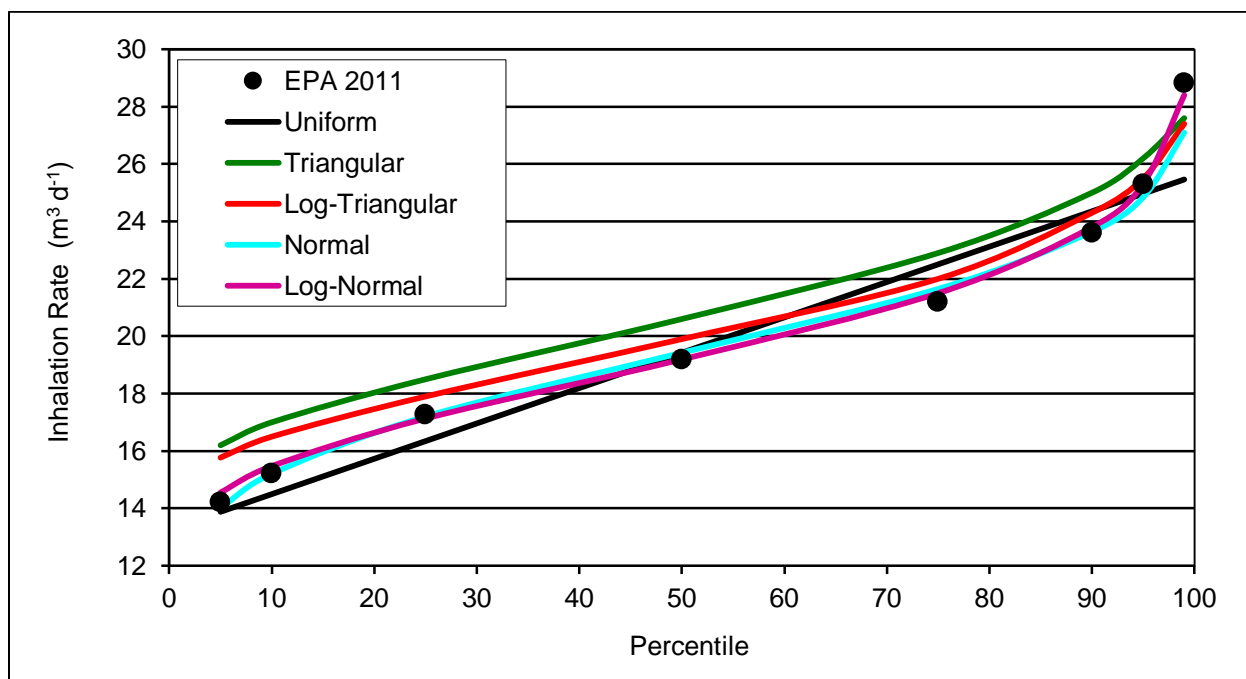
The time spent outdoors for pregnant women is assumed to be the same as for adults at Yokota AB from Chehata et al. (2013). A log-triangular distribution with a minimum of 0.25 h, a mode of 1 h, and a maximum of 17 h was used to represent the time spent outdoors for pregnant women.

##### **5.3.2.2 Protection Factors**

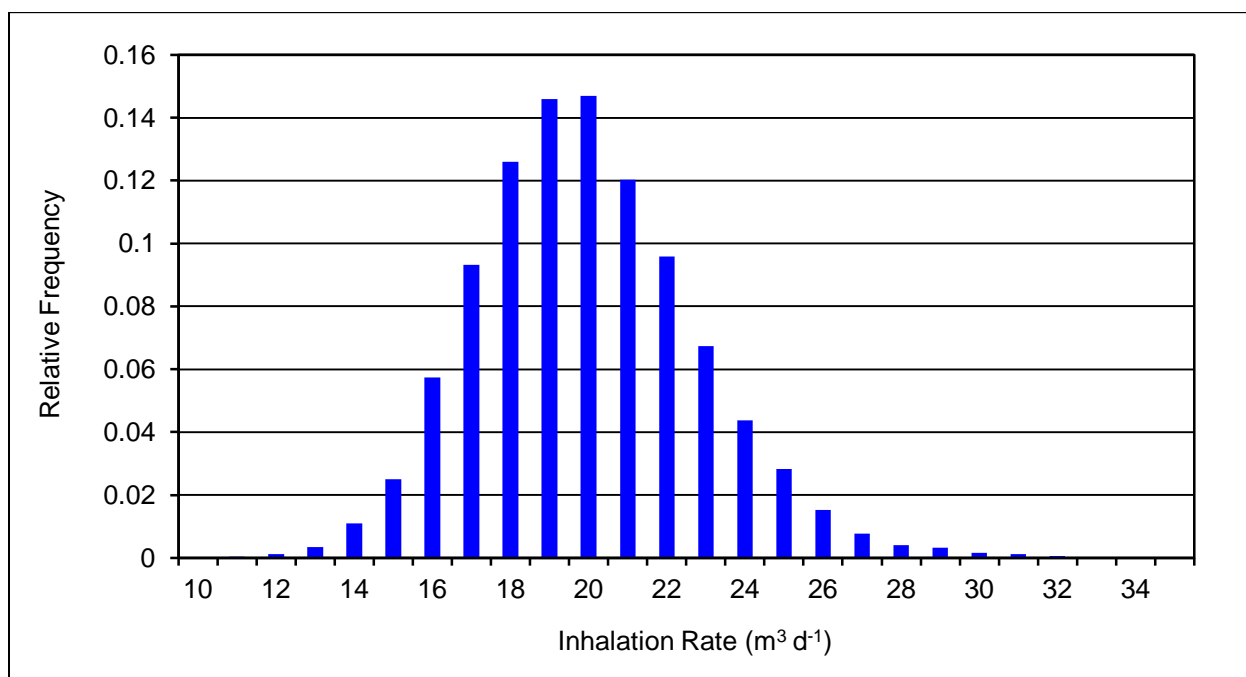
The types of structures a pregnant woman occupied while indoors affect the dose from exposure to external radiation. Structures of different types and sizes provide varying degrees of protection from radiation emitted by radioactive materials found out of doors. A protection factor, defined as the ratio of the outdoor to indoor dose rates, quantifies the degree of radiological protection afforded by various structures. The distributions of protection factors used for buildings at Yokota AB in Chehata et al. (2013) were used in this probabilistic analysis. Numerical distributions of protection factors were used for both residential and non-residential buildings. For residential buildings, the mean protection factor is 4.7 and the corresponding 95<sup>th</sup> percentile is 6.2. For non-residential buildings, the mean protection factor is 11 and the corresponding 95<sup>th</sup> percentile is 22.

##### **5.3.2.3 Air Inhalation Rate**

The average daily inhalation rate distribution for pregnant women was estimated using the statistical data from the EPA (2011). Table 6-54 of that report contains percentile inhalation rate data for pregnant women at the time of conception and at 9, 22, and 36 weeks after conception for the age groups of 11 to 23, 23 to 30, and 30 to 55 years old. The mean breathing rate for each of the four time periods was calculated and used in a statistical analysis to produce the arithmetic mean and the 5<sup>th</sup>, 10<sup>th</sup>, 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, 90<sup>th</sup>, 95<sup>th</sup>, and 99<sup>th</sup> percentile values for the distribution. Normal, log-normal, uniform, triangular, and log-triangular distributions were fitted to these statistical data to determine the best fit. The fitted distributions are shown in Figure 6. The log-normal distribution was determined to best fit the average EPA statistical data. The geometric mean of the log-normal distribution is 19.2 m<sup>3</sup> d<sup>-1</sup> and the geometric standard deviation is 1.2. The relative frequency distribution of the daily inhalation rate for pregnant women is shown in Figure 7.



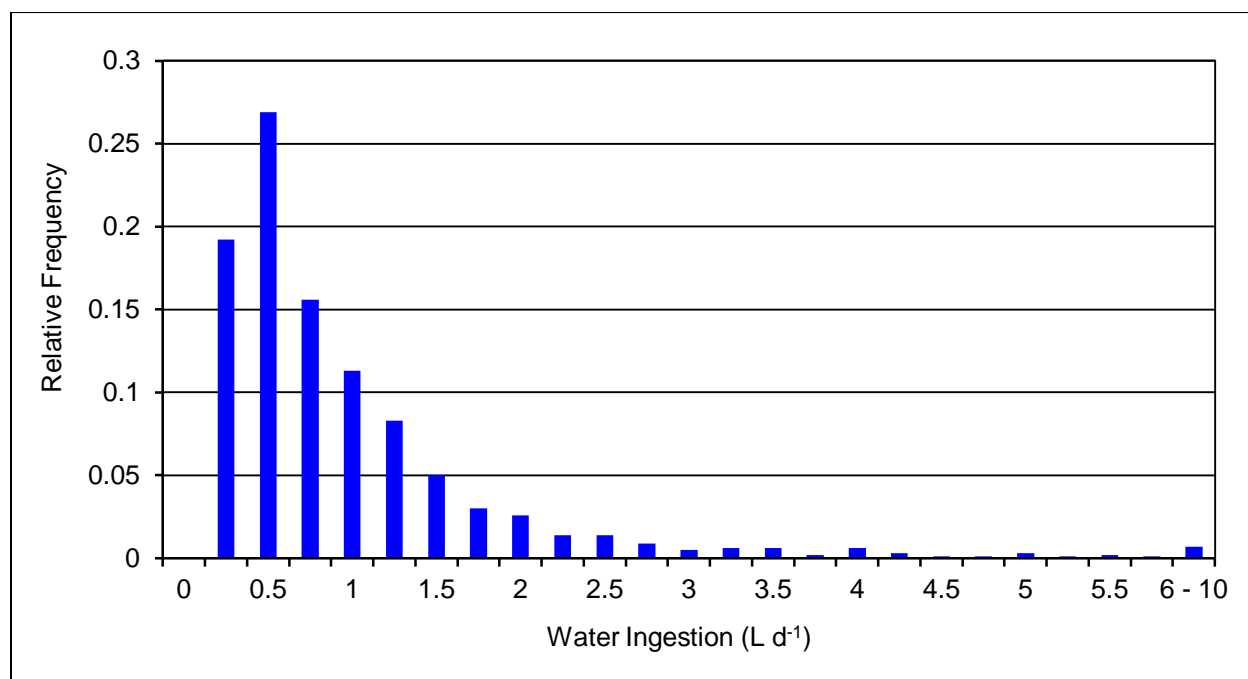
**Figure 6. Cumulative probability distribution functions fitted to the published statistical data of inhalation rates for pregnant women**



**Figure 7. Relative frequency distribution of the average daily inhalation rate for pregnant women**

#### 5.3.2.4 Drinking Water Ingestion Rate

The water ingestion rate for pregnant women was estimated using statistical data published by the EPA (EPA, 2004). Table 6.3.B1 of that report contains the arithmetic mean, the geometric mean, and the 90<sup>th</sup> and 95<sup>th</sup> percentile values of the average daily ingestion rate of pregnant women from direct and indirect intake of drinking water. The geometric mean, the 90<sup>th</sup> percentile, and 95<sup>th</sup> percentile were graphed on a log-normal probability plot. Examination of the log-normal probability plot indicated that the distribution of daily drinking water intake was consistent with a log-normal distribution for pregnant women. The geometric mean and 95<sup>th</sup> percentile were then used to create a log-normal distribution. The geometric mean of the log-normal distribution for the average daily water ingestion is 0.56 L d<sup>-1</sup> and the geometric standard deviation is 2.6. The relative frequency of the probability distribution of the daily water ingestion rate for pregnant women is shown in Figure 8.



**Figure 8. Relative frequency distribution of the average daily water ingestion rate for pregnant women**

#### 5.3.2.5 Soil and Dust Ingestion Rate

Absent statistical data of soil and dust ingestion rates that are specific to pregnant women, and having found that in general the dose from this pathway is very small with insignificant sensitivity to the total dose (Chehata et al., 2013), the same distribution of ingestion rate of soil and dust for adults at Yokota AB is used. A triangular distribution for incidental soil and dust ingestion was used with a minimum of 0.01 g d<sup>-1</sup>, a mode of 0.05 g d<sup>-1</sup>, and a maximum of 0.2 g d<sup>-1</sup>.



### 5.3.3. Dose Coefficients for the Embryo/Fetus

Distributions of DC functions for both inhalation and ingestion were developed for the 18 isotopes listed in Table 1. For 14 of these isotopes, in all their chemical forms, the ICRP (2003a) DCs for acute intakes at conception and 5, 10, 15, 25, and 35 weeks after conception were used to create time-dependent functions. The results for the DCs of the isotopes that contribute most to inhalation dose are plotted in Figure 9 to Figure 12.

For I-130 in all its chemical forms, La-140, Rb-86, and Te-129, where ICRP inhalation DCs were unavailable, the values for 35 weeks after conception were obtained from the United Kingdom Health Protection Agency and were used in the deterministic estimations. For the probabilistic analysis, the values of the DCs for 35 weeks after conception for La-140, Rb-86, and Te-129 were assumed to be the same for all times. These time-dependent estimates of DCs are appropriate because it is assumed that the DCs do not vary more than an order of magnitude over the entire time of pregnancy based on the DC of similar isotopes. The DCs for 35 weeks after conception for aerosol, gaseous methyl iodide, and gaseous elemental I-130 were scaled to other time periods using the corresponding DCs for I-131. These time-dependent estimates of DCs are appropriate because the uptake and metabolism by pregnant women of I-130 is identical to I-131.

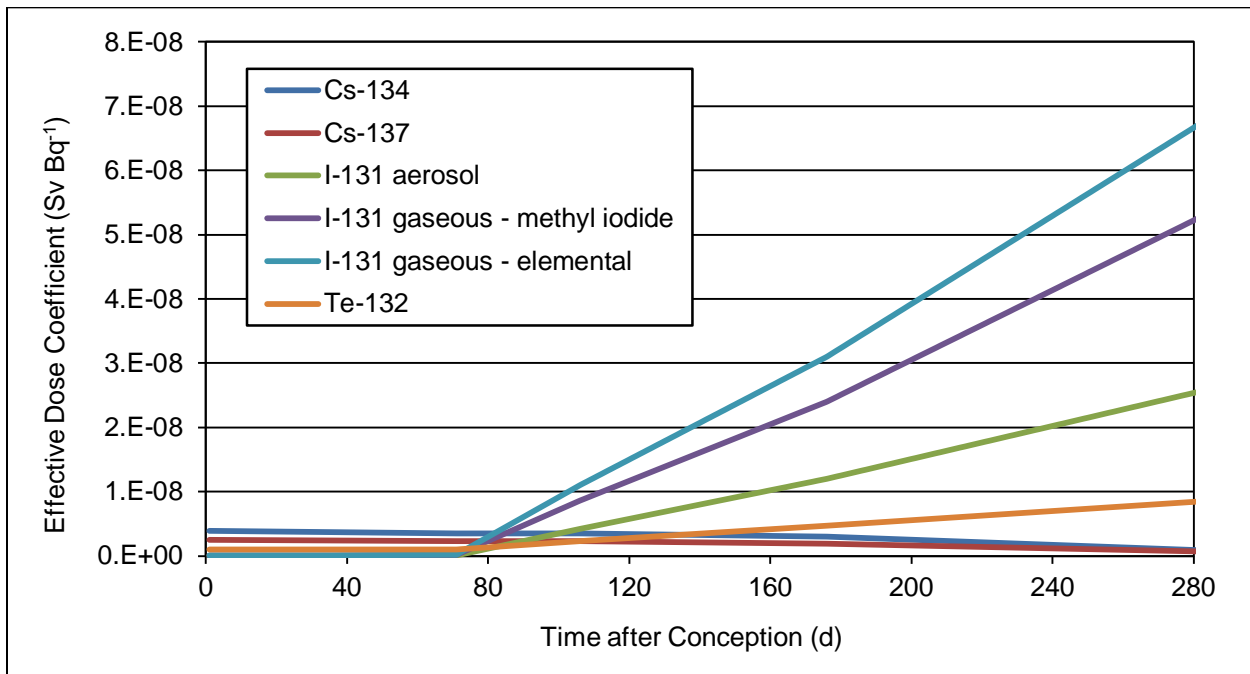
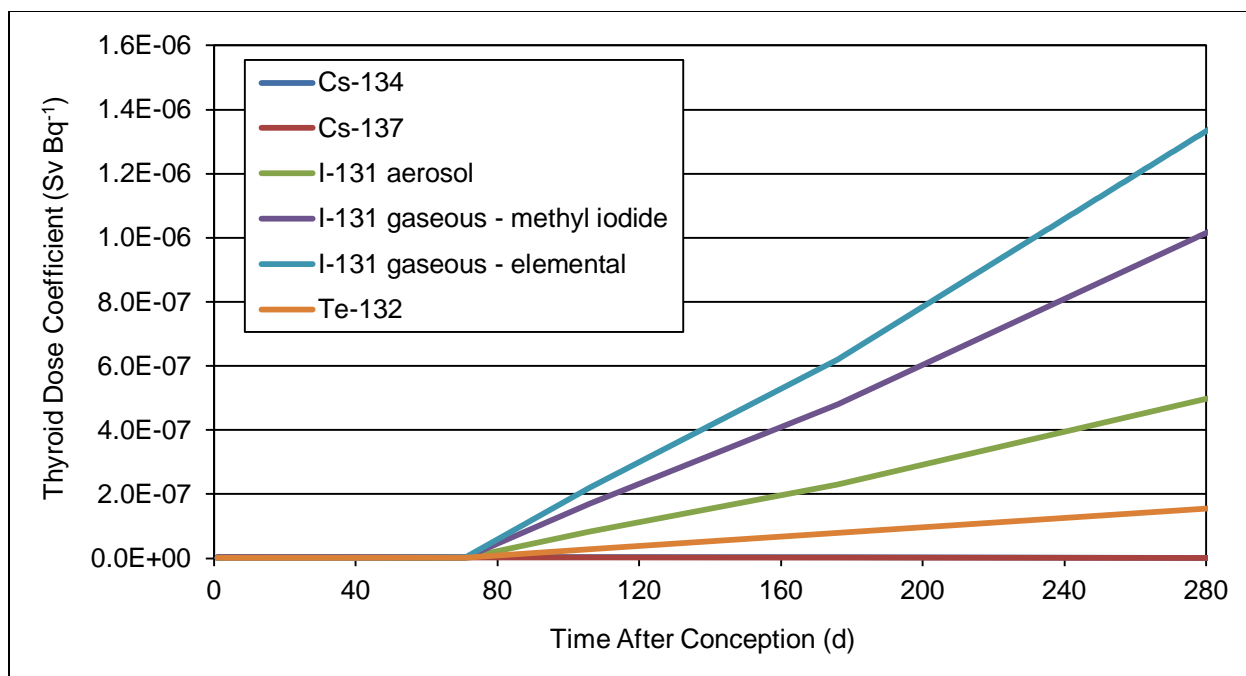
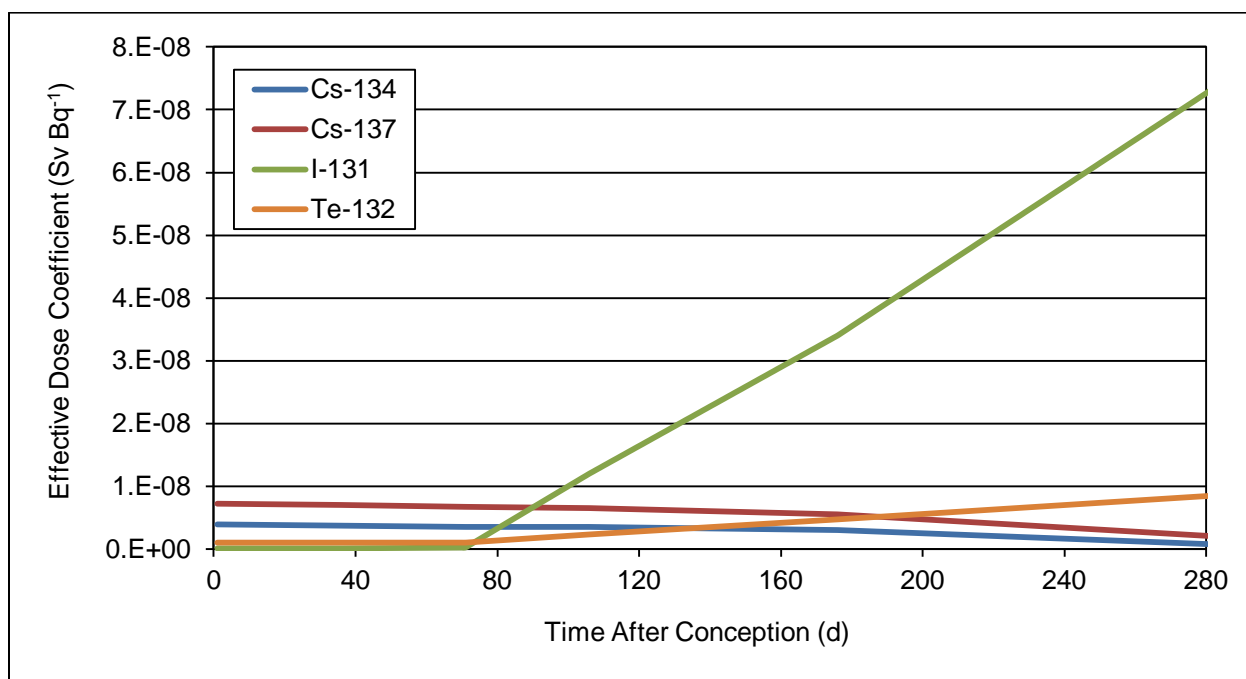


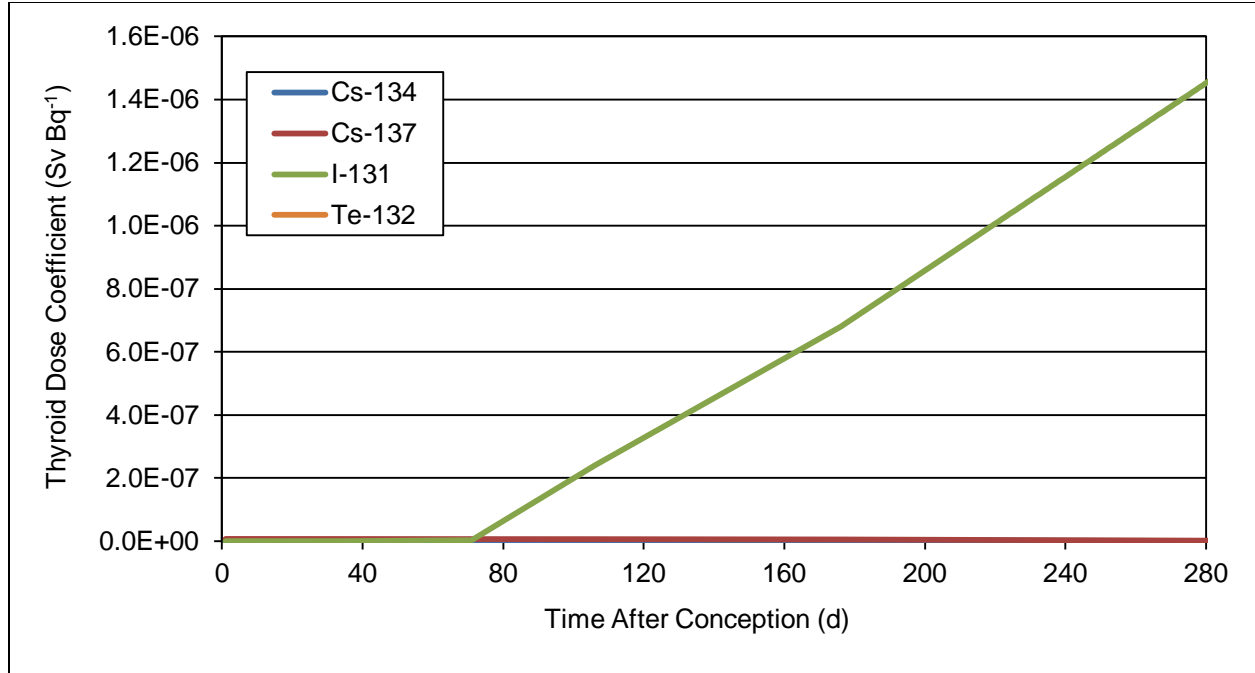
Figure 9. Effective dose coefficients for the embryo/fetus from inhalation



**Figure 10. Thyroid dose coefficients for the embryo/fetus from inhalation**



**Figure 11. Effective dose coefficients for the embryo/fetus from ingestion**



**Figure 12. Thyroid dose coefficients for the embryo/fetus from ingestion**

It should be noted that plots for all of the radionuclides listed in the legend of Figure 12 are not apparent. This is because all but the one for I-131 are superimposed near the baseline value of 0.0.

#### 5.3.4. Randomized Day of Conception

To account for the possible dates of conception, a new parameter is introduced that accounts for the number of days since conception ( $d_c$ ) prior to March 11, 2011. For the probabilistic analysis, the possible range of the number of days since conception is from 0 to 203. This range was chosen so that a woman is pregnant during the two-month period used in the deterministic analysis. Under this assumption, a  $d_c$  value of 0 represents a conception date of March 11, 2011, and a  $d_c$  value of 203 represents a conception date of August 20, 2010. A uniform distribution with a minimum of 0 d and a maximum of 203 d was used to model this parameter.

The number of days since conception is used to ensure that the values of DCs and the values of the concentrations of inhaled or ingested radionuclides represent the same day. In this probabilistic analysis, Equation 3 from Chehata et al. (2013) is modified to Equation 3:

$$E_{Inh} = V_{Air} \sum_j \left( \int_{t_{start}}^{t_{end}} C_{Air_j}(t) DC_{Inh_j}(t + d_c) dt \right) \quad (3)$$

where:

$E_{Inh}$	=	Either the committed effective dose or the committed equivalent dose to the thyroid from inhalation of radioactive materials (Sv).
$V_{Air}$	=	Effective volume of contaminated air inhaled per day for each activity level that accounts for diminished air activity concentration while present indoors ( $m^3 d^{-1}$ ).
$t$	=	The date variable for calculation of dose (d).
$t_{start}$	=	Beginning time of exposure (d).
$t_{end}$	=	End time of exposure (d).
$C_{Air j}(t)$	=	Measured or modeled air activity concentration outdoors for radionuclide $j$ at time $t$ ( $Bq m^{-3}$ ).
$d_c$	=	The number of days since conception prior to March 11, 2011 (d).
$DC_{Inh j}(t+d_c)$	=	The time-dependent DC for the embryo/fetus due to intake of the pregnant mother ( $Sv Bq^{-1}$ ).

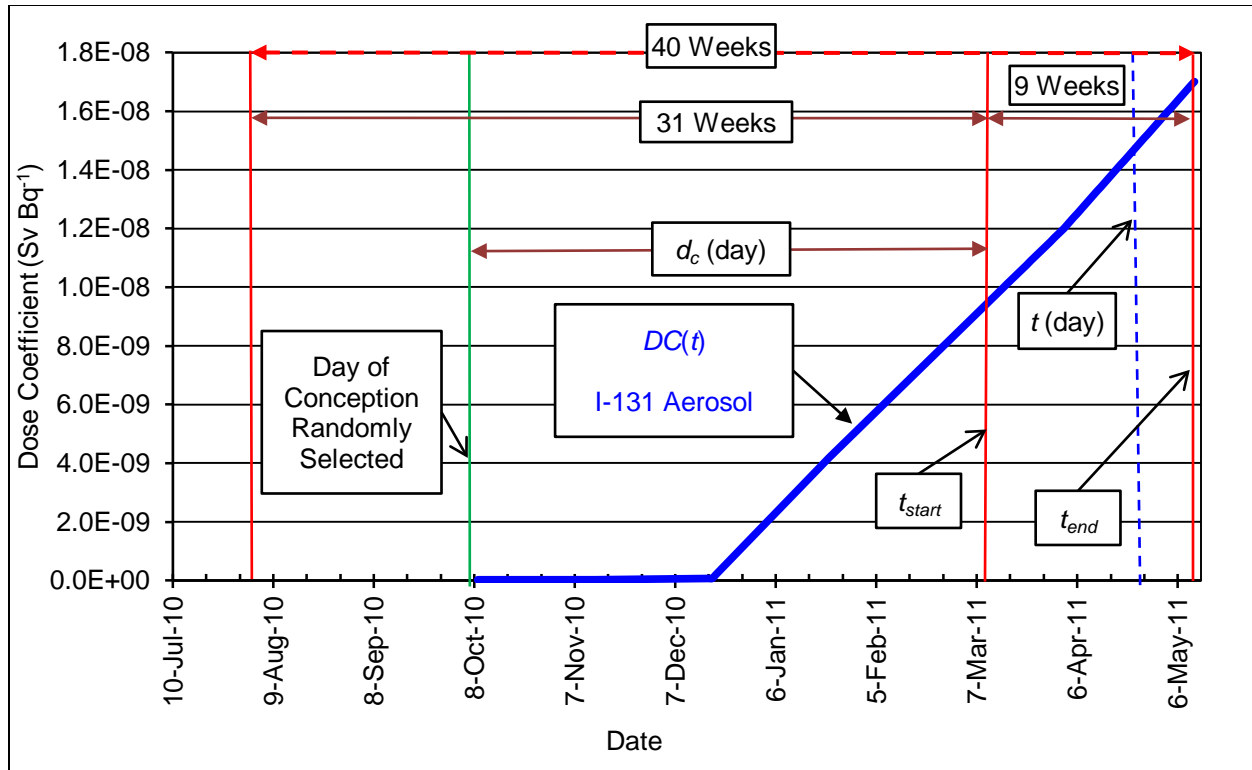
The number of days since conception is assumed to be uncorrelated with all other parameters in the dose calculations.

The concept of using a moving time-dependent embryo/fetus DC and the number of days since conception is shown in Figure 13. The same concept is used to determine the dose to the embryo/fetus from the ingestion of radionuclides in drinking water or in contaminated soil and dust.

## 5.4 Results and Discussions

### 5.4.1. Results of the Probabilistic Analysis

All doses were calculated by means of a probabilistic analysis model using Monte Carlo simulation with 10,000 histories (repetitions). All analyses were made using Mathcad<sup>®</sup> software and random Monte Carlo sampling. The external dose, the committed effective dose and the committed equivalent dose to the thyroid from intakes for each internal exposure pathway were calculated. The committed doses are to age 70 for the embryo/fetus. Dose components were then added to estimate the total effective dose and the total equivalent dose to the thyroid. The geometric mean, arithmetic mean, 95<sup>th</sup> percentile, and the adjustment factor were determined for all dose pathways. In this analysis, the geometric mean is used as the central estimate because the geometric mean is considered to be a more representative measure of central tendency for highly-skewed distributions such as those for the calculated doses. The uncertainty factor is defined as the ratio of the 95<sup>th</sup> percentile and the geometric mean values of the dose distributions. The statistical results of the probabilistic analyses for each exposure pathway and the total doses are given in Table 12. The frequency distributions for the total effective dose and total equivalent dose to the thyroid are shown in Figure 14 and Figure 15.



**Figure 13. Model of a moving time-dependent embryo/fetus dose coefficient function based on a randomized day of conception**

**Table 12. Dose results for adults at embryo/fetus using probabilistic analysis**

Exposure Pathway	Geometric Mean Dose (mSv [rem])	Arithmetic Mean Dose (mSv [rem])	95 <sup>th</sup> Percentile Dose (mSv [rem])	Uncertainty Factor
External	0.015 [0.0015]	0.017 [0.0017]	0.031 [0.0031]	2.1
<b>Committed Effective Dose</b>				
Inhalation	0.011 [0.0011]	0.027 [0.0027]	0.099 [0.0099]	9.0
Water ingestion	0.002 [0.002]	0.005 [0.005]	0.020 [0.002]	10
Soil ingestion	<0.001 [<0.001]	<0.001 [<0.0001]	<0.001 [<0.0001]	7.2
<b>Total*</b>	<b>0.034 [0.0034]</b>	<b>0.047 [0.0047]</b>	<b>0.14 [0.014]</b>	<b>4.0</b>
<b>Committed Equivalent Dose to the Thyroid</b>				
Inhalation	0.054	0.36 [0.036]	1.5 [0.15]	28
Water ingestion	0.013	0.089 [0.0089]	0.37[0.037]	29
Soil ingestion	<0.001	0.001 [0.0001]	0.004[0.0004]	14
<b>Total*</b>	<b>0.15 [0.015]</b>	<b>0.47 [0.047]</b>	<b>1.9[0.19]</b>	<b>12</b>

\*The total dose includes the external dose and the committed internal dose from all internal exposure pathways.

#### 5.4.2. Comparison of Doses using Probabilistic Analysis and Deterministic Methods

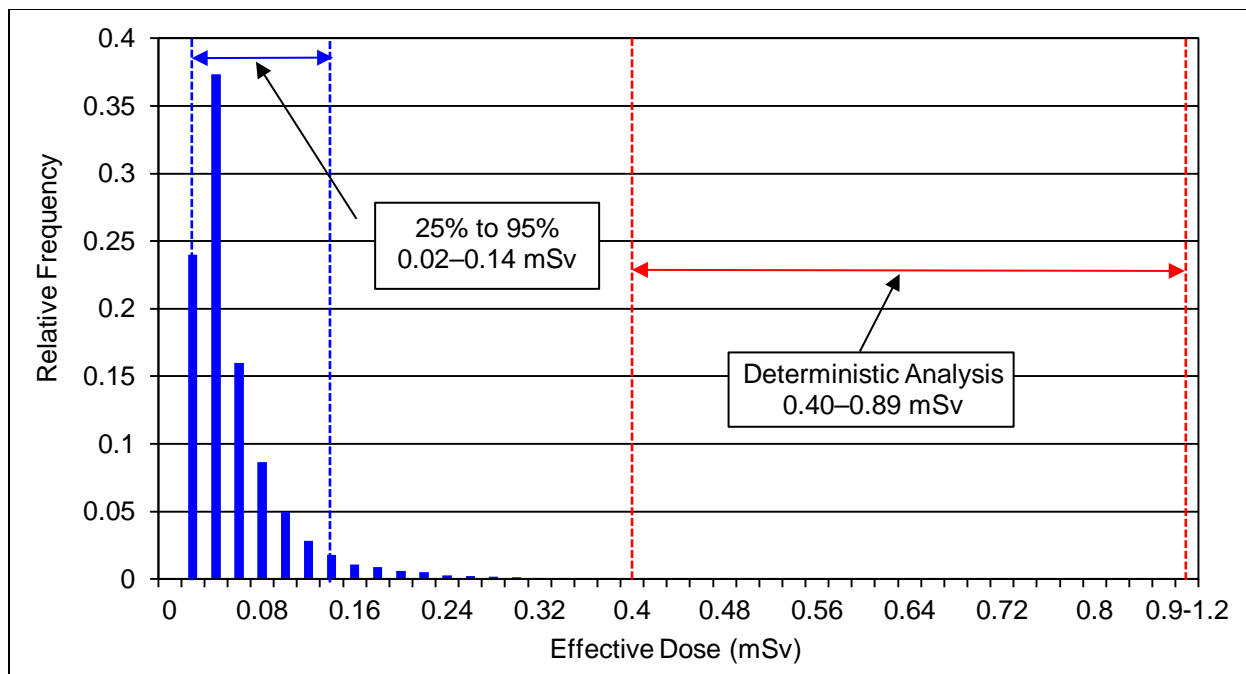
The total effective dose and total equivalent dose to the thyroid estimated by deterministic and probabilistic methods for an embryo/fetus at Yokota AB are listed in Table 13. Also shown is the equivalent percentile rank of the doses estimated by deterministic methods within the probabilistic dose distributions. Finally, the ratio of the doses estimated by deterministic methods to the 95<sup>th</sup> percentile doses of the probabilistic distributions are calculated and displayed in Table 13. A ratio greater than 1.0 indicates that the dose estimated by deterministic methods exceeds the 95<sup>th</sup> percentile value of the probabilistic dose estimates and is conservative, i.e., estimated to be higher than the doses received by all or nearly all fetuses and nursing infants.

**Table 13. Comparison of doses estimated by deterministic methods with the 95<sup>th</sup> percentile doses from probabilistic analysis for the embryo/fetus at Yokota AB**

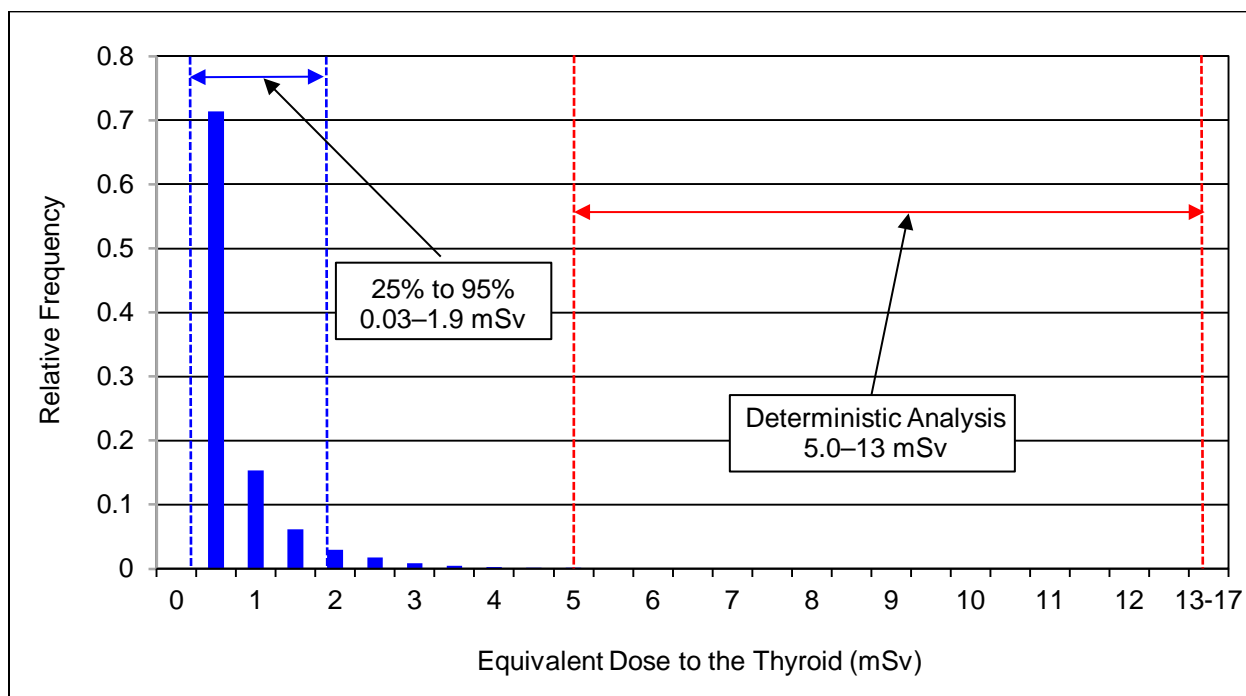
<b>Dose</b>	<b>Dose Estimated by Deterministic Methods * (mSv)</b>	<b>Probabilistic 95<sup>th</sup> Percentile Dose (mSv)</b>	<b>Dose Estimated by Deterministic Methods as Percentile of the Probabilistic Distribution</b>	<b>Ratio of Deterministic Analysis to 95<sup>th</sup> Percentile Dose</b>
Total effective dose	0.89	0.14	99.9	6.5
Total equivalent dose-thyroid	13	1.9	99.9	6.8

\* These doses are estimated by deterministic methods provided in Section 3 of this report.

Figure 14 and Figure 15 show a comparison of doses estimated by deterministic methods and the doses from the probabilistic analysis. The dose distributions calculated using the probabilistic analysis are shown as histograms. Vertical lines representing the 25<sup>th</sup> and 95<sup>th</sup> percentile doses are also shown. The range of doses estimated by deterministic methods for the embryo/fetus at Yokota AB, using various time spent indoors, inhalation rates, and water and soil ingestion rates, given in Table 6, are also shown in Figure 14 and Figure 15. The 25<sup>th</sup> percentile probabilistic level was chosen as a comparison to the lowest dose estimated by deterministic methods because that percentile was considered representative of the lower end of the EPA parameter distributions used in the deterministic analysis to develop various high-sided dose parameter values.



**Figure 14. Distribution of total effective dose from probabilistic analysis and range of doses estimated by deterministic methods for the embryo/fetus at Yokota AB**



**Figure 15. Distribution of total equivalent dose to the thyroid from probabilistic analysis and range of doses estimated by deterministic methods for the embryo/fetus at Yokota AB**

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## Section 6.

### Discussion

#### 6.1 Summary of Dose Results

Table 14 summarizes the effective whole body and thyroid doses for both the embryo/fetus and nursing infant for all DARWG locations (excluding D-2 through D-7) and exposure conditions.

**Table 14. Summary of the doses to the embryo/fetus and nursing infant**

<b>Group</b>	<b>Total Effective Dose (mSv [rem])</b>	<b>Thyroid Dose (mSv [rem])</b>
Embryo/fetus	0.01–0.89 [0.001–0.089]	0.04–12 [0.004–1.2]
Nursing Infant	0.02–1.3 [0.002–0.13]	0.04–21 [0.004–2.1]

Although the ranges of doses in Table 14 cover the ranges of time spent indoors and physical activity levels, they are still conservative in that high-sided parameter values, including a multiplicative adjustment factor of three for the DCs for Cs, I, and Te were used to calculate the doses.

#### 6.2 Using the Dose Results

The assumptions used in estimating the doses in this report were chosen to produce conservative values for location-based populations. It is expected that the results of an assessment for any specific embryo/fetus or nursing infant would be less than the highest dose in this report for any given location. As such, the doses in this report should not be used for estimates of the risk of adverse health effects for individuals. However, these results can be used as the initial step of a future dose reconstruction or assessment for a specific embryo/fetus or nursing infant. Dose assessments for a specific embryo/fetus or nursing infant would require detailed information about the exposure conditions (location, time, and radiological environment).

According to the ICRP (2007a), “The main and primary use of effective dose is to provide a means of demonstrating compliance with dose limits.” The effective dose is intended to limit adverse health effects such as cancer and inherited disorders and is intended to apply to age and sex averaged populations. Although effective dose can be used for initial studies and hypothesis generation, it is not the correct quantity for epidemiological studies of radiation risk (ICRP, 2007a). Because of these and other limitations, it is not appropriate to “calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long times [collective effective dose]” (ICRP, 2007a). The ICRP (2007a) suggests that, “In retrospective assessments of doses to specified individuals that may substantially exceed dose limits, effective dose can provide a first approximate measure of the overall detriment.” In this sense, effective dose can

provide a broad indication of potential risks within a given population exposed to radiation. However, greater care must be exercised when attempting to determine risks to a specific embryo/fetus or nursing infant.

Although organ doses can, in principle, be used to estimate risks to individuals (ICRP 2007a and NCRP, 2009a), the thyroid doses reported here should not be used to estimate individual risks. The thyroid doses in this report were calculated under an assumption of dose maximizing conditions, hence they are inappropriate for estimating risks to a specific embryo/fetus or nursing infant. Furthermore, risks to the thyroid from external irradiation and radioiodine intake depend on the age at exposure, internal or external radiation exposure, gender, amount of stable iodine in the diet<sup>23</sup>, and time since exposure (NCRP, 2008).

### 6.3 Probabilistic and Uncertainty Analyses

The UF for the probabilistic analysis of the external dose for the embryo/fetus at Yokota AB is 2.1, which is consistent with the value reported in Chehata et al. (2013) for this location. The UFs for the internal doses due to the intake of radioactive materials from inhalation, ingestion of water, and incidental ingestion of soil and dust range from about 7 to 29. The UFs for the probabilistic total effective dose and total equivalent dose to the thyroid are about 4 and 12, respectively. The magnitude of the UFs for the total doses depends on the contributions from the external versus internal doses with the higher UFs being associated with higher contributions from internal doses. This is expected because internal dose models use parameters with broader uncertainty distributions than external dose models. In this analysis, the 95<sup>th</sup> percentile external dose is about 20 percent of the 95<sup>th</sup> percentile of the total effective dose, and the UF is about 4. However, the 95<sup>th</sup> percentile external dose is less than 2 percent of the 95<sup>th</sup> percentile total equivalent dose to the thyroid and the UF is about 12.

The ratios of the doses estimated by deterministic methods to the 95<sup>th</sup> percentile doses from the probabilistic distributions are greater than 1. This indicates that the doses estimated by deterministic methods are greater than the corresponding 95<sup>th</sup> percentile doses from the probabilistic analysis. Moreover, the percentile rank of the total effective dose and total equivalent dose to the thyroid, estimated by deterministic methods, are at the 99.9 percent level. Therefore, DARWG concludes that the doses estimated in Section 3 for the embryo/fetus at Yokota AB are sufficiently conservative and capture the total estimated doses for all or nearly all of the population of concern. As a result of the probabilistic analysis of embryo/fetus doses for Yokota AB reported in this section, it is possible to infer that the doses calculated by deterministic methods for other locations evaluated in Section 3 are sufficiently conservative and exceed the 95<sup>th</sup> percentile confidence level. This inference is appropriate given the similarity in the uncertainty distributions for the dose input parameters at other DOD locations where pregnant women were present. Based on all conducted probabilistic assessments (here in Section 3 and Chehata et al. 2013), there are no additional significant sources of uncertainties in the doses of the unstudied groups that would cause the deterministic analyses to produce high-doses that are greater than the 95<sup>th</sup> percentile of the probabilistic analyses. In addition, it is expected that if the same probabilistic methodology is applied with similar and realistic parameter uncertainty distributions and assumptions at other locations, the high-sided conservative assumptions used in the deterministic method calculations would produce similar

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<sup>23</sup> This modification of risk is in addition to stable iodine's role in blocking radioiodine uptake by the thyroid (NCRP, 2008).

results, i.e., maximum doses that are higher than the 95<sup>th</sup> percentile values of the probabilistic distributions.

#### 6.4 Comparison of Nursing Infant Doses with Other Analyses

To help assess the validity of the nursing infant doses, they are compared here with doses from other analyses. As part of its international role in emergency response the World Health Organization (WHO) prepared a report, *Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami*, which summarized both effective and thyroid doses for 1 year old infants, 10 year old children, and adults for the first year of exposure after the accident (WHO, 2012). Cassata et al. (2012) calculated effective and thyroid doses to various age groups for two months of exposure from March 12 to May 11, 2011.

Table 15 shows the comparisons among the nursing infant doses calculated in this report, children (Cassata et al., 2012), and infants (1 y), children (10 y), and adults in the “rest of Japan” for an exposure period of 1 year (WHO, 2012 and Chehata, 2012)<sup>24</sup>. The doses calculated in this report and Cassata et al. (2012) are based on exposures, excluding food consumption, over the two-month OTR period of March 12 to May 11, 2011, whereas the WHO (2012) assessment calculates doses from 1 year of exposure including food consumption. Furthermore, this report and Cassata et al. (2012) include UFs of three applied to the DCs for Cs, I, and Te; WHO (2012) does not apply such factors.

With the exception of doses at Misawa AB, most of the radiation doses from this report were from intakes of radioactive material. This is evident in the large differences between the effective and thyroid doses. The thyroid dose is roughly a factor of 10–20 larger than the effective dose for most of the locations. However, at Misawa AB this ratio is about two. Most of the radiation dose at Misawa AB is from external radiation exposure, which results in the effective and thyroid doses being approximately equal. The interested reader should refer to Cassata et al. (2012) for the external radiation doses at other DARWG locations.

The DC UFs are used to account for uncertainties in the dose from inhalation and ingestion of radioactive material and are included in the doses calculated here and in Cassata et al. (2012). However, the WHO (2012) report presents central estimates of doses. To best compare the values, it’s useful to compare the doses without the use of an UF. An approximate adjustment can be made by reducing the doses in Table 15 for the nursing infants and children by about three<sup>25</sup>. If the UFs are removed from the calculation of the doses for nursing infants and children in Table 15, then the doses calculated by the DARWG fall into or below the dose bands reported in WHO (2012) and therefore are in general agreement with the low doses determined by WHO.

The DARWG in Cassata et al. (2012) calculated the doses to an infant (0 to 1 y age group) based on the infant’s own exposure, which did not include intakes of breast milk. In this report, the total dose to a nursing infant is calculated from the intake of mother’s milk, the

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<sup>24</sup> Other differences between the WHO (2012) and DARWG reports (this report and Cassata et al., 2012) are discussed in Chehata (2012).

<sup>25</sup> Because the total radiation dose is a sum of the internal and external components and the adjustment factors apply only to the DCs (internal radiation dose), a simple multiplicative factor cannot be strictly applied. However, roughly 90 percent or more of the dose, in most cases, is from internal radiation exposure, so for rough comparisons a simple factor of 3 can be used.

external radiation dose to the infant, and the infant's own inhalation of air, ingestion of soil, and consumption of  $0.4 \text{ L d}^{-1}$  of water to ensure that  $1.2 \text{ L d}^{-1}$  of total fluid is consumed (see Section 4.3.1 and Appendix C.).

**Table 15. Comparison of this report's nursing infant doses with Cassata et al. (2012) and WHO (2012)**

DARWG Location (No.)	This Report		Cassata et al. (2012)		WHO (2012)	
	Nursing Infant <sup>*</sup>		Children <sup>†</sup>		Infants, Children, Adults <sup>‡</sup>	
	Total Effective Dose (mSv)	Thyroid Dose (mSv)	Total Effective Dose (mSv)	Thyroid Dose (mSv)	Total Effective Dose (mSv)	Thyroid Dose (mSv)
Misawa AB (D-1)	0.07	0.16	0.06–0.07	0.08–0.15	0.1–1	1–10
Yokota AB (D-8)	1.3	21	0.53–0.99	5.1–14		
Akasaka Press Center (D-9)	1.2	21	0.44–0.90	5.0–14		
Atsugi NAF (D-10)	1.1	18	0.39–0.82	4.1–12		
Yokosuka NB (D-11)	1.0	18	0.33–0.77	4.1–12		
Camp Fuji (D-12)	0.37	6.1	0.15–0.35	1.9–6		
Iwakuni MCAS (D-13)	0.05	0.89	0.02–0.05	0.28–0.87		
Sasebo NB (D-14)	0.07	1.1	0.03–0.07	0.35–1.1		

<sup>\*</sup> These doses include contributions from mother's radionuclide intakes as described in Section 2.2.4, the infant's intake of air, soil, 0.4 L d<sup>-1</sup> of water and 0.8 L d<sup>-1</sup> of mother's milk (See Section 4.3.1.), and external radiation exposure under maximum exposure conditions. Also, an adjustment factor of three was applied to the DCs of Cs, I, and Te used to calculate the internal radiation dose.

<sup>†</sup> These doses were calculated for all age groups (0 to 1 y, >1 y to 2 y, >2 y to 7 y, >7 y to 12 y, and >12 y to 17 y) assuming no time spent indoors and highest physical activity levels as discussed in Cassata, et al. (2012). An adjustment factor of 3 was applied to the DCs of Cs, I, and Te (Cassata et al., 2012). The highest values for children occurred for the >1 y to 2 y age group.<sup>‡</sup> These doses were estimated for infants (1 y), children (10 y), and adults in the "rest of Japan" for an exposure period of 1 year as described in WHO (2012). No adjustment factors were applied to the DCs used in the WHO report. Sendai Airport is located in the Miyagi prefecture and is considered one of the "neighboring Japanese prefectures" in the WHO report (WHO, 2012).

## 6.5 Reports Related to Radionuclides in Human Breast Milk in Japan

### 6.5.1. Ingestion Intakes of I-131 in Tokyo

Murakami and Oki (2012) examined the ingestion intake of I-131 by the citizens (adults, children, and infants) of Tokyo from March 21, 2011, to March 20, 2012. The authors calculated, through deterministic calculations, the average and maximum thyroid doses (based on assuming that all intakes were from materials with the highest measured I-131 concentrations) including the effects of countermeasures (Murakami and Oki, 2012). The authors also estimated the doses from March 18–20, 2011, although they considered these results “uncertain” because monitoring data of sufficient quantity and quality were not available (Murakami and Oki, 2012). Without countermeasures<sup>26</sup> for March 18, 2011 to March 20, 2012, the average thyroid dose to an infant was 2.79 mSv, and the maximum thyroid dose was 107 mSv, with about 90 percent of the dose being delivered within the first 2 weeks of exposure (Murakami and Oki, 2012). The authors assumed the following ingestion rates for infants<sup>27</sup>: drinking water from all sources  $0.82 \text{ kg d}^{-1}$ , milk and dairy products  $0.6 \text{ kg d}^{-1}$ , and for vegetables the ingestion rate was not given (but the reader was referred to supplemental material). The assessment used individuals living on the economy near Tokyo, so this population is not representative of the DOD-affiliated population that is the subject of this report for whom it is assumed dose from food intake was negligible. For infants and children, the major contribution to the thyroid dose was the intake of milk and dairy products followed by drinking water, and spinach consumption. For adults and children, drinking water was the largest source of I-131 in the diet followed by spinach and dairy consumption. Drinking water is included in this report and in Cassata et al. (2012). The ingestion of breast milk was not considered in Murakami and Oki (2012).

### 6.5.2. I-131 in Mother’s Milk in Japan, April and May 2011

Unno et al. (2012) examined I-131 concentrations in mother’s milk specimens collected in April and May of 2011; they also evaluated mother’s milk collected by a citizens group during March and April of 2011. The I-131 concentration was measured in 126 specimens collected between April 24 and May 31, 2011 from 119 volunteers living within 250 km of the FDNPS (Unno et al., 2012). The correlation between I-131 concentration in mother’s milk and environmental media was also investigated. In April 2011, 23 women submitted breast milk specimens; of these, 7 contained detectable levels of I-131: 2.2 to  $8.0 \text{ Bq kg}^{-1}$ . In May 2011 none of the remaining 96 women had I-131 in their breast milk specimens<sup>28</sup> (Unno et al., 2012). Based on this evidence, the authors conclude that I-131 in the environment can be transferred to mother’s milk (Unno et al., 2012). The authors also examined data from 28 women who participated in an independent project from March 24 to April 29, 2011 sponsored by a group of Japanese citizens. In this group, specimens from 6 of 28 women had detectable<sup>29</sup> levels of I-131: 6.4 to  $36.3 \text{ Bq kg}^{-1}$  (Unno et al., 2012). No radiation doses were calculated by Unno et al. (2012).

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<sup>26</sup> Countermeasures include food distribution restrictions and the distribution of bottled water for infants (Murakami and Oki, 2012).

<sup>27</sup> No distinction between nursing and non-nursing infants was given in Murakami and Oki (2012).

<sup>28</sup> The detection limits for this set of measurements was given as  $1.6 \pm 0.3 \text{ Bq kg}^{-1}$  (Unno et al., 2012).

<sup>29</sup> The detection limit this set of measurements was reported as  $4.0\text{--}7.6 \text{ Bq kg}^{-1}$  (Unno et al., 2012).

The data in Unno et al. (2012) show that the I-131 concentration in drinking water decreases much more quickly than simple radioactive decay would predict<sup>30</sup>. The authors also note that the concentration of I-131 in drinking water and vegetables (and to a lesser degree chicken eggs and cow's milk) was much higher before March 22, 2011, than after. (Unno et al., 2012) They conclude that “nursing infants may also have been exposed to large doses before March 22” (Unno et al., 2012). The typical diet in Japan differs from the typical diet in the U.S. in many ways, but, importantly, the Japanese diet contains higher amounts of iodine. The Japanese population, on average, ingests about 1–3 mg d<sup>-1</sup> of iodine (Zava and Zava, 2011 and FAO, 2001), whereas for the U.S. population the average intake of iodine is about 140–500 µg d<sup>-1</sup> (NIH, 2011 and FAO 2001). A higher intake of stable iodine would, in general, reduce the radiation dose to a nursing infant because of reductions in the fraction of I-131 transferred to breast milk. Finally, Unno et al. (2012) note that because the participants in the study might have been more concerned about the effects of I-131 in mother's milk, these participants might not have been representative of the breastfeeding mothers.

The measured I-131 concentrations in mother's milk were quite low with many non-detectable levels for a geographically widespread population. However, given the lack of information about mothers' intakes of I-131 before March 22, 2011, the assumptions needed to estimate the I-131 concentrations in mother's milk over time, differences in daily iodine intake between U.S. and Japanese diets, and the representativeness of the study participants when comparing them to the DOD-affiliated POI, the DARWG refrained from estimating potential radiation doses for nursing infants using data from Unno et al. (2012).

### **6.5.3. Media Reports about the Radionuclide content in Mother's Milk in Japan**

There have been media reports about the radionuclide content in the breast milk of Japanese women. Several examples are:

- “No radioactivity found in Fukushima mothers' breast milk” was reported in November by The Asahi Shimbun (2012). This story reports that Fukushima prefectural government officers reported that no radioactive cesium was measured in 378 breast milk specimens. No referral to an official report was given.
- “Japan planning breast milk radiation tests” reported by Kyung Lah of CNN in January 2012 (Lah, 2012). Here it is reported that “A government study found traces of radioactive cesium in the breast milk of 7 mothers.” No referral to the study is given, although there are some similarities to Unno et al. (2012).
- “Small amounts of iodine found in breast milk” reported in the Japan Times in April 2011 (Japan Times, 2011). Although no citation or web link is given, this is clearly a summary of the citizens' group data<sup>31</sup>, which is discussed in Unno et al. (2012) and summarized above.
- “Minute levels of radiation detected in breast milk” reported originally by NHK<sup>32</sup>. The story was reported by several other new agencies; for example, the Laaska News and Analysis

<sup>30</sup> This is likely caused by the mixing of less contaminated source water in to the municipal water system.

<sup>31</sup> Unno et al. (2012) refers the reader to <http://bonyuutyousa.net/>; however, the site is in Japanese.

<sup>32</sup> NHK is the Japan Broadcasting Corporation, which identifies itself to English speaking audience by the pronunciation of the initials N-H-K. The link to the original news story is given as [http://www3.nhk.or.jp/daily/english/30\\_22.html](http://www3.nhk.or.jp/daily/english/30_22.html) but as of February 11, 2013 the link was broken.

(Laaska News, 2011), which cites the NHK story. It's stated (Laaska News, 2011) that Japan's Health Ministry<sup>33</sup> reported "a minute amount of radioactive materials in breast milk in 7 mothers in central and northeastern Japan." For Iwaki City in the Fukushima prefecture, breast milk specimens from one mother contained 3.5 Bq kg<sup>-1</sup> of "radioactive iodine" and 2.3 Bq kg<sup>-1</sup> of "radioactive cesium" (Laaska News, 2011). The article continues and states that "up to 2.8 becquerel of radioactive materials per kilogram were also detected in 6 mothers in 2 other prefectures" (Laaska News, 2011).

Taken as a whole these media reports reinforce the lack of data regarding the transfer of radionuclides released during the FDNPS accident to human breast milk.

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<sup>33</sup> Japan has no "Ministry of Health." The appropriate ministry is Ministry of Health, Labour and Welfare: <http://www.mhlw.go.jp/english/>. A search of the site could find no information similar to this media report.



## Section 7.

### Conclusions

This report describes the assessment of potential radiation doses to the embryos/fetuses and nursing infants carried by, or nursed by, members of the DOD-affiliated population who were subject to exposure from radioactive materials released during the Fukushima Daiichi Nuclear Power Station (FDNPS) accident during the two-month OTR period of March 12 through May 11, 2011. Conservative estimates of representative radiation doses were calculated using high-sided parameter values at different locations throughout Japan, but mainly emphasizing the prefectures of Aomori, Kanagawa, Nagasaki, and Tokyo where most of the DOD-affiliated population was concentrated. DOD-affiliated individuals in the Okinawa prefecture were not included because external radiation dose rates there remained indistinguishable from background during the OTR period (Cassata et al., 2012).

In radiation protection, it is acknowledged that the embryo and fetus are radiosensitive during the entire developmental period (NCRP, 1977 and ICRP, 2003b) but not more so than the child (Boice, 2012). One purpose of this report is to present the approach, methods, and results of an initial study to estimate conservative radiation doses that are likely greater than the true radiation doses received by any specific embryo/fetus or nursing infant from radioactive materials released during the FDNPS accident. The NCRP's Scientific Committee 6-8 reviewed this report and concurred that the "high sided doses in this report are likely greater than any embryo, fetus, or nursing infant would have received." The probabilistic and uncertainty analysis conducted for this report indicates that this goal was achieved and confirmed that the methods used to estimate the doses in this report are very conservative. Based on the results of the probabilistic and uncertainty analysis, the radiation doses summarized below are higher than the 95<sup>th</sup> percentile values of the probabilistic distributions presented in this report.

For all included DARWG locations, a two-month exposure period, and all exposure conditions:

- For the embryo/fetus, the total effective doses were calculated to be about 0.01 to 0.89 mSv (0.001 to 0.089 rem), and the thyroid doses ranged from about 0.04 to 12 mSv (0.004 to 1.2 rem).
- For a nursing infant, the total effective doses were calculated to be about 0.02 to 1.3 mSv (0.002 to 0.13 rem), and the thyroid doses ranged from about 0.04 to 21 mSv (0.004 to 21 rem).

Because of the high-sided nature of the doses calculated for this report, it would be inappropriate to use these doses to estimate the probability of an adverse outcome to a specific embryo/fetus or nursing infant. There is "no convincing direct evidence" of inherited disease in children that can be said to be caused by either parent's exposure to ionizing radiation before conception (NCRP, 2013). At doses less than about 100 mSv (10 rem) to the embryo/fetus, increased risks of mental retardation, birth defects, and other adverse health outcomes are small (or possibly zero) and have not been observed in humans (NCRP, 2013). The potential radiation risk to a specific embryo, fetus, or nursing infant must have an estimate of the actual dose made by a qualified

expert<sup>34</sup>, and this dose must be evaluated in conjunction with a physician who specializes in prenatal or early childhood radiation risks.

The staff of the DOD BIHR has examined preliminary data on identified pregnant women and rates of birth defects during OT (Conlin et al., 2013). The BIHR staff, for identified pregnant women, determined the rates of pregnancy loss, live births, and birth defects. Roughly 600 total pregnancies were identified during the OT period; of these, there were about 560 confirmed live births. For infants (about 520 with enough information to be included in the analysis), the total rate of adverse health outcomes was consistent with historical BIHR data. (Conlin et al., 2013). Additional studies are being planned by BIHR to better identify the population of women and infants and to follow live-born infants through at least their first year of life.

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<sup>34</sup> NCRP (2013) defines a qualified expert for the purposes of its report as “a person having the knowledge and training to measure radiation, to evaluate radiation safety techniques, and to advise regarding radiation protection needs.” The definition also includes a list of the professional certifications required to be a qualified expert.

## Section 8.

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## Appendix A.

### Radiological Quantities and Units

#### A-1. Introduction

To determine human radiation exposures quantitatively and to provide for radiation protection, radiological quantities and units are needed. The ICRP has developed a system of units for use in radiation protection (ICRP, 2007a). Within the ICRP system, several radiological quantities are of particular interest for this report: absorbed dose, equivalent dose, effective dose, radioactivity, and activity. This appendix presents a brief review of radiological quantities and units. For details about the radiological quantities and terms used in this report, see Cassata et al. (2012).

#### A-2. Absorbed dose

In radiation protection, the fundamental quantity of concern is the absorbed dose (ICRP, 2007), which “is the amount of energy absorbed by that organ or tissue divided by its weight.” (WHO, 2012) The SI unit for organ dose is joule per kilogram ( $\text{J kg}^{-1}$ ) and is given the special name gray (Gy). In the United States, the older unit for absorbed dose, rad, is used;  $1 \text{ rad} = 0.01 \text{ Gy}$ .

#### A-3. Equivalent dose

The sensitivity of specific tissues and organs to radiation exposure depends on the type of radiation. To account for this sensitivity, the quantity equivalent dose was developed. The equivalent dose to a tissue or organ is the absorbed dose to that tissue or organ multiplied by a radiation weighting factor that depends on the type of radiation, such as alpha particles or gamma-ray photons (WHO, 2012). The special name for the SI unit of equivalent dose is the sievert (Sv). In the United States, the older unit for equivalent dose (and older name dose equivalent), rem, is used;  $1 \text{ rem} = 0.01 \text{ Sv}$ . Often, the equivalent dose is called an organ dose. Sometimes, and in this report in particular, the organ is named; for example thyroid dose.

#### A-4. Effective dose

In addition to radiation dependent sensitivity, each tissue or organ in the body has an inherent sensitivity to the stochastic effects<sup>35</sup> of radiation exposure. When considering the radiation exposure to the whole body, the concept of effective dose was developed. The effective dose is the sum of the products of equivalent dose to each organ multiplied by a tissue weighting factor (WHO, 2012). The special name for the SI unit of effective dose is the sievert (Sv). In the United States, the older unit for effective dose (and older name effective dose equivalent), rem, is used;  $1 \text{ rem} = 0.01 \text{ Sv}$ . For doses from radiation sources outside the body (external radiation dose) in the absence of internal radiation dose, the external radiation dose is about equal to the

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<sup>35</sup> Examples of stochastic effects are cancer in the person exposed and effects appearing in offspring of the person exposed (heritable effects) (ICRP, 2007).

effective dose<sup>36</sup>. In practice, the external radiation dose is estimated from personal radiation monitors (dosimeters), by measurements of the external radiation field (surveys), or from knowledge of the radiation sources in the area. It's usually assumed that the whole body received a uniform radiation dose as determined from dosimeters, surveys, or calculations.

The effective dose replaced the quantity “effective dose equivalent” (EDE)<sup>37</sup> in the 1990 recommendations of the ICRP (ICRP, 1991). In its 1990 recommendations with the introduction of the effective dose, the ICRP did not recommend attempts to change earlier values of the EDE to effective doses. In addition, the Commission stated that values of the effective dose equivalent can be added to values of effective doses “without any adjustment.” (ICRP, 1991) The effective dose and equivalent dose “provide a basis for estimating the probability of stochastic effects only for doses well below the threshold for deterministic effects” and “are intended for use in radiation protection, including the assessment of risk in general terms.” (ICRP, 1991)

#### **A-5. Committed dose**

To describe the radiation dose from intakes of radioactive material (internal radiation dose), the radiation protection community uses the concept of the “committed dose.” Committed dose is a radiation protection quantity<sup>38</sup> (ICRP, 2007a) and means that the radiation doses from intakes of radioactive materials are calculated based on the behavior of the radioactive material in a reference person<sup>39</sup> for a specified period after an intake: 50 years (adults) after an intake, until age 70 (children), the first 8 weeks of gestation, and from the 9<sup>th</sup> to 38<sup>th</sup> week of gestation. Although the radiation doses are actually delivered over time after an intake, this committed dose is associated with the time the intake occurred.

#### **A-6. Activity and radioactivity**

The amount of radioactive material at a given time is given by the number of atoms or by the mass of that material. The activity is the rate at which radioactive transformations are taking place. (ICRU, 2011) In contrast, radioactivity is a property of matter and refers to the events associated with nuclear transformations. (ICRU, 2011) The SI unit of activity is one transformation per second ( $s^{-1}$ ) and is given the special name becquerel (Bq). The older unit for activity used in the U.S. is the curie (Ci); 1 Ci = 37 billion Bq.

#### **A-7. Quantities used in this report**

As discussed in Cassata et al. (2012), the quantities calculated in this report are the effective and equivalent dose to the thyroid (called the thyroid dose in this report) as presented in ICRP Publication 60 (ICRP, 1991) and used in the ICRP databases of dose coefficients (DC) (ICRP, 2003 and 2007b). Although effective dose is a radiation protection quantity and not usually used in retrospective dose assessments other than for comparisons with dose limits or

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<sup>36</sup> For the external radiation dose to be equal to the effective dose, the body must be irradiated uniformly by the external source of radiation.

<sup>37</sup> The term EDE is still used by the U. S. Government in its regulations.

<sup>38</sup> Radiation protection quantities, such as committed effective dose, are meant to be used for planning, justification and optimization of radiation protection practices, and demonstrating compliance with regulations; they are not meant for epidemiology studies or specific investigations of individual risk (ICRP, 2007a).

<sup>39</sup> The “reference person” is a hypothetical construct “for whom the organ or tissue equivalent doses are calculated by averaging the corresponding doses of the Reference Male and Reference Female.” (ICRP, 2007a)

action levels (ICRP, 2007a), the effective dose is useful in a preliminary assessment (NAS, 1995).

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## Appendix B.

### DARWG Locations

The DARWG noted that DOD-affiliated individuals were concentrated at certain sites located throughout Japan, and so the DARWG created 14 broad-based locations (called DARWG locations) from the 63 sites so that a location-based dose estimate could be prepared for each location. The DARWG locations were constructed based on (Cassata et al., 2012):

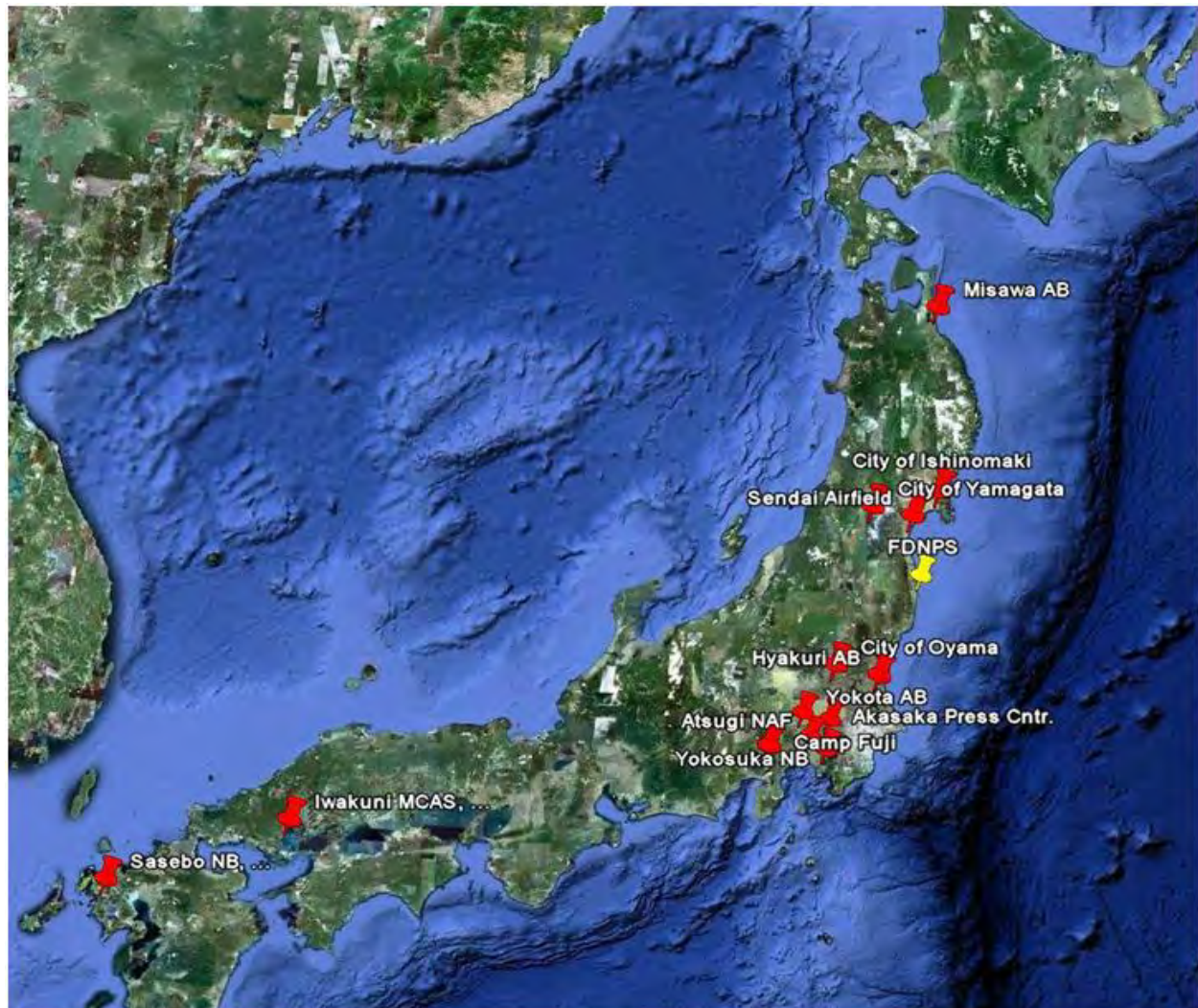
- location relative the FDNPS,
- environmental data quality and availability,
- population density, and
- topography.

A principal site was identified for each location which was based on the DOD-affiliated population density and location of most environmental monitoring. The principal site was used as the primary identifier for each location. Table B-1 lists each DARWG location, its DARWG number, the prefecture of the nearest MEXT station, and the distance from the FDNPS.

**Table B-1. DARWG locations and distance from the FDNPS**

<b>DARWG Location</b>	<b>DARWG Number</b>	<b>DOD-Affiliated Population Associated with the DARWG Location</b>	<b>Prefecture</b>	<b>Distance from FDNPS (km)</b>
Misawa AB	D-1	8,368	Amori	368
Sendai Airport	D-2	No permanent DOD-affiliated population	Miyagi	81
City of Ishinomaki	D-3		Miyagi	116
City of Yamagata	D-4		Yamagata	111
J-Village	D-5		Fukushima	20
Hyakuri AB	D-6		Ibaraki	148
City of Oyama	D-7		Tochigi	165
Yokota AB	D-8	7,907	Tokyo	240
Akasaka Press Center	D-9	25	Tokyo	229
Atsugi NAF	D-10	9,039	Kanagawa	261
Yokosuka NB	D-11	16,449	Kanagawa	266
Camp Fuji	D-12	160	Shizuoka	305
Iwakuni MCAS	D-13	5,402	Yamaguchi	874
Sasebo NB	D-14	5,959	Nagasaki	1130

Figure B-1 from Cassata et al. (2012) shows the location of the principal site for each DARWG location and the location of the FDNPS and is included to show the relative distance and direction of each DARWG location from the FDNPS.



**Figure B-1. Principal site (red pin) of each of the 14 DARWG locations and FDNPS**

## Appendix C.

### Parameter Values Used to Account for Lifestyle Differences

The information in this section was adapted from Cassata et al. (2012) and provides parameter values that were used to calculate radiation doses based on other than dose maximizing conditions. All parameter values were allowed to vary for the mothers and nursing infants when appropriate.

The time spent indoors was stratified into four categories: none, lower, mean, and upper. The latter three categories correspond to the lower bound of the 5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup> percentile values of the time spent indoors from EPA (2011). The levels of physical activity used for the intake rates were inactive, low activity, medium activity, and high activity. These levels are the upper bound of the 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 95<sup>th</sup> (or upper percentile) values of the intake rates. The parameter values are summarized below.

**Table C-1. Summary of parameter values used to account for lifestyle differences**

Parameter	Description	Infant	Mother
Time Spent Indoors (min d <sup>-1</sup> )	None	0	0
	Lower	579	330
	Mean	1108	833
	Upper	1440	1288
Breathing Rate (m <sup>3</sup> d <sup>-1</sup> )	Inactive	3.69	15.59
	Low Activity	4.22	17.48
	Medium Activity	4.75	19.38
	High Activity	9.2	30.0
Drinking Water Ingestion Rate (L d <sup>-1</sup> )	Inactive	NA *	0.939
	Low Activity		1.345
	Medium Activity		1.877
	High Activity		4.0
Soil Ingestion Rate (mg d <sup>-1</sup> )	Inactive	16.8	16.8
	Low Activity	60	100
	Medium Activity	200	200
	High Activity	1000	200

\* See text for a discussion. In Cassata et al. (2012) the water ingestion rate for the 0 to 1 year age group was 0.384–1.2 L d<sup>-1</sup>.

The use of the ICRP DCs sets the intake rate of mother's milk to 0.8 L d<sup>-1</sup> and the maximum value for the total fluid for a nursing infant was assumed to be 1.2 L d<sup>-1</sup>; therefore, any variation in the infant's water ingestion rate would be 0–0.4 L d<sup>-1</sup>. In Cassata et al. (2012), the minimum water intake for an infant is 0.384 L d<sup>-1</sup>. Because it is reasonable to assume that a

nursing infant would ingest water or fluids other than mother's milk and the difference between 0.384 and 0.4 L d<sup>-1</sup> is trivial, it was decided to hold an infant's water intake to 0.4 L d<sup>-1</sup> to calculate the infant's direct exposure.



## Appendix D.

### Dose Consequences for Exposure after May 11, 2011

#### D-1. Assumptions

The exposure to radiation and intakes of radioactive material did not stop on May 11, 2011. To assess the radiological consequences of these extended exposures, the DARWG examined the potential doses arising from living in, on, or near the DARWG locations from May 12, 2011, through March 6, 2012 (300 days).

This appendix explicitly shows the calculation for the embryo/fetus, but it is expected that the residual dose to a nursing infant would follow a similar trend.

To calculate the embryo/fetus dose from this residual exposure, the following were assumed.

1. Because the contribution to the total external dose rate from each radionuclide is unknown and this calculation is meant to be a conservative estimate of radiation doses, the external radiation dose rate calculated from the average radiation dose rate between May 4 and May 11, 2011 was assumed to remain constant over the 300-day period.
2. Because estimates of each radionuclide's contribution to the internal radiation dose are available (Cassata et al., 2012) each radionuclide's contribution to the internal dose is considered separately and is assumed to decrease from radioactive decay only.
  - a. The only radionuclides of concern for internal radiation dose assessment from May 11, 2011 forward are Cs-134, Cs-137, I-131, and Te-129m.
  - b. Sr-89, Sr-90, and Cs-136 are neglected because their dose contributions ( $\sim 10^{-15}$  to  $10^{-13}$  Sv d<sup>-1</sup>) are about two to four orders of magnitude smaller than those for the next largest dose contribution (Te-129m,  $\sim 10^{-11}$  Sv d<sup>-1</sup>). Also, their concentrations in air, water, and soil are much smaller than the concentrations of Cs-134, Cs-137, I-131, and Te-129m on May 11, 2011, if they are present at all. (Cassata, et al., 2012).
3. There were neither major releases nor changes in environmental conditions during the 300 day period.
4. The intake rates remain the same as discussed in Section 2.2.4.

#### D-2. Yokosuka Naval Base

Yokosuka NB was chosen as the representative location to assess residual radiation exposure beyond the end date of the Operation Tomodachi Registry, May 11, 2011, because about 16,000 people were stationed at Yokosuka NB, which represents about 30 percent of the shore-based population under consideration. This large, stable population with embryo/fetus radiation doses in the middle of the range of all the radiation doses makes Yokosuka NB a reasonably representative location for this assessment.

### D-3. Calculations

#### D-3.1. External Radiation Dose

The total external dose contribution to both the effective and thyroid doses is estimated as the average daily radiation dose rate between May 4 and May 11, 2011, multiplied by 300.

The average external radiation dose rate at Yokosuka NB from May 4 through May 11, 2011, was about  $1.6 \mu\text{Sv d}^{-1}$  and was relatively constant. See Figure D-1 below, which is based on data from Cassata et al. (2012) with negative net values set to zero;  $1.6 \mu\text{Sv d}^{-1}$  is about equal to  $0.006 \text{ mR h}^{-1}$ . This yields a total external dose of 0.48 mSv for May 12, 2011, through March 6, 2012, (300 days) with no accounting for changes over time.

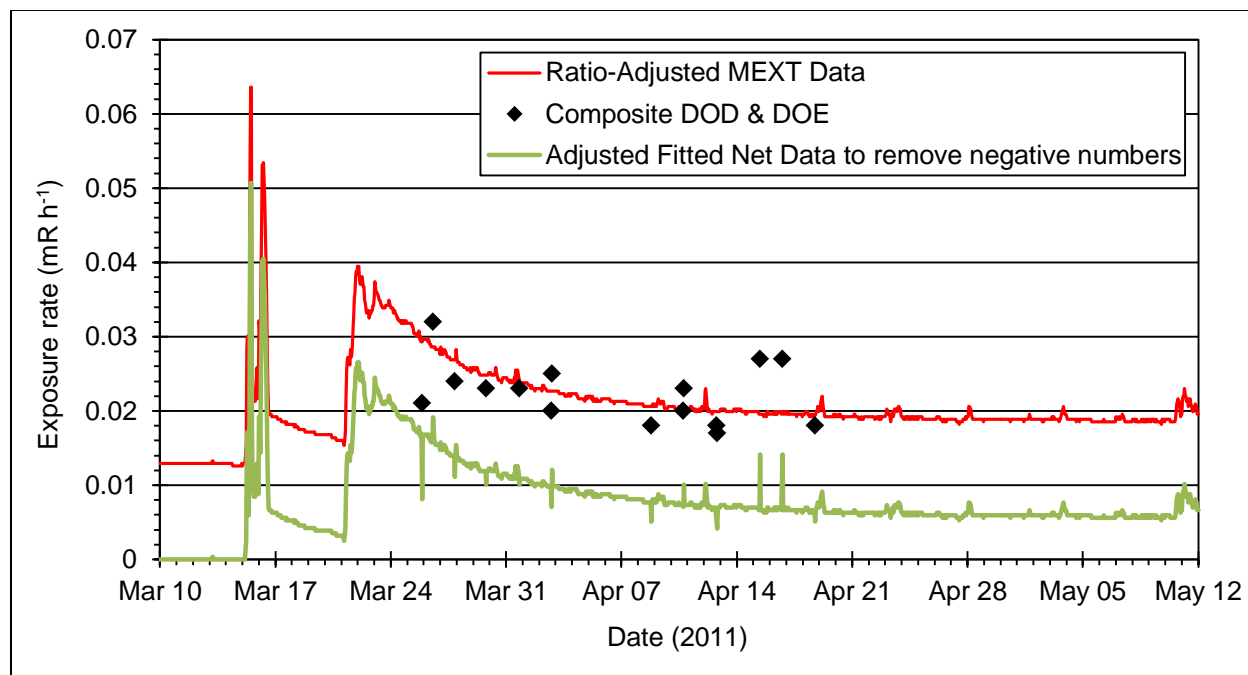


Figure D-1. External exposure rate data for Yokosuka NB

#### D-3.2. Internal Radiation Dose

To estimate the overall internal radiation dose from air inhalation, water ingestion, and soil ingestion, the dose contribution between May 4 and May 11, 2011 from each of these environmental pathways was investigated.

As discussed in Appendix C of Cassata et al. (2012), all dose calculations were performed on an hourly basis; however, if only daily measurements were made, they were converted to hourly values. The result of this is that both hourly and daily values for each of the environmental pathways were available. By the beginning of May most of the dose values were based on either daily measurements or extrapolated values (Cassata, et al., 2012).

For calculating the internal dose component, the total dose was found by integrating the daily dose rate for each environmental pathway and for the following radionuclides Cs-134, Cs-137, I-131, and Te-129m:

$$H_{Int,i} = \dot{H}_{0,i} \int_0^T e^{-\lambda_i t} dt \quad (D-1)$$

where:

- $H_{int,i}$  = The committed effective<sup>40</sup> or thyroid dose arising from a 300-day exposure from intakes of radionuclide  $i$  (Cs-134, Cs-137, I-131, and Te-129m) starting on May11, 2011 (mSv);
- $\dot{H}_{0,i}$  = The daily effective or thyroid dose rate on May 11, 2011, for radionuclide  $i$  (mSv d<sup>-1</sup>); and,
- $\lambda_i$  = The decay constant for radionuclide  $i$  (d<sup>-1</sup>).

Solving equation (D-1) for T = 300 days yields equation (D-2) for the internal radiation dose for each radionuclide.

$$H_{Int,i} = \dot{H}_{0,i} \left( \frac{1 - e^{-\lambda_i(300)}}{\lambda_i} \right). \quad (D-2)$$

The total internal radiation dose is calculated by summing equation (D-2) over Cs-134, Cs-137, I-131, and Te-129m. The exponential factor on the right hand side of the equation depends only on the radionuclide and is the decay correction factor. The decay correction factors for Cs-134, Cs-137, I-131, and Te-129m are shown in Table D-1.

**Table D-1. Decay correction factors**

Radionuclide	Physical Decay Constant (d <sup>-1</sup> )	Decay Correction Factor (d)
Cs-134	$9.26 \times 10^{-4}$	262
Cs-137	$6.33 \times 10^{-5}$	297
I-131	$8.62 \times 10^{-2}$	12
Te-129m	$2.04 \times 10^{-2}$	49

Table D-2 shows the internal radiation dose contributions extrapolated to March 6, 2012 at Yokosuka NB data for Cs-134, Cs-137, I-131, and Te-129m. For all radionuclides the internal radiation doses from water ingestion was zero. The internal dose contributions are trivial.

<sup>40</sup> Equations (D-1) and (D-2) apply to the effective dose, E, and the thyroid dose, H. However, only H is shown for convenience.

**Table D-2. Internal embryo/fetus dose contributions between May 11, 2011 and March 6, 2012 at Yokosuka NB**

Radionuclide	Medium	Total Effective Dose			Thyroid Dose		
		$\dot{E}_{0,i}$ (mSv d <sup>-1</sup> )* (11 May 2011)	$E_{int}^{\dagger}$ (mSv)	Radionuclide Subtotal (mSv)	$\dot{H}_{0,i}$ (mSv d <sup>-1</sup> )* (11 May 2011)	$H_{int}^{\dagger}$ (mSv)	Radionuclide Subtotal (mSv)
Cs-134	Air	$2.5 \times 10^{-7}$	$6.6 \times 10^{-5}$	$2.8 \times 10^{-4}$	$2.4 \times 10^{-7}$	$6.3 \times 10^{-5}$	$2.8 \times 10^{-4}$
	Soil	$8.3 \times 10^{-7}$	$2.2 \times 10^{-4}$		$8.3 \times 10^{-7}$	$2.2 \times 10^{-4}$	
	Water	0	0		0	0	
Cs-137	Air	$2.0 \times 10^{-7}$	$5.9 \times 10^{-5}$	$2.7 \times 10^{-4}$	$1.8 \times 10^{-7}$	$5.3 \times 10^{-5}$	$2.5 \times 10^{-4}$
	Soil	$7.1 \times 10^{-7}$	$2.1 \times 10^{-4}$		$6.6 \times 10^{-7}$	$2.0 \times 10^{-4}$	
	Water	0	0		0	0	
I-131	Air	$1.3 \times 10^{-6}$	$1.6 \times 10^{-5}$	$3.2 \times 10^{-5}$	$1.6 \times 10^{-5}$	$1.9 \times 10^{-4}$	$5.2 \times 10^{-4}$
	Soil	$1.3 \times 10^{-6}$	$1.6 \times 10^{-5}$		$2.7 \times 10^{-5}$	$3.2 \times 10^{-4}$	
	Water	0	0		0	0	
Te-129m	Air	$1.7 \times 10^{-7}$	$8.3 \times 10^{-6}$	$8.3 \times 10^{-6}$	$3.0 \times 10^{-8}$	$4.5 \times 10^{-7}$	$1.5 \times 10^{-6}$
	Soil	0	0		0	0	
	Water	0	0		0	0	
Total				$5.9 \times 10^{-4}$		Total	$1.1 \times 10^{-3}$

\* These dose values are from the dose calculations in Cassata et al. (2012).

† The decay correction factors used are shown in Table D-1.

### **D-3.3. Total Residual Radiation Doses**

The effective whole body dose from exposure to residual radioactive materials is calculated to be 0.48 mSv (0.48 mSv from external radiation exposure and  $5.9 \times 10^{-4}$  mSv from internal radiation exposure). The thyroid dose is also 0.48 mSv (0.48 mSv from external radiation exposure and  $1.1 \times 10^{-3}$  mSv from internal radiation exposure). With respect to a nursing infant the inhalation and ingestion DCs are similar, and so, the radiation dose would be expected to accumulate in a manner similar to the embryo/fetus. External radiation exposure dominates both the effective and thyroid doses; therefore, it is expected that the residual dose to both embryo/fetus and nursing infant would be similar.

### **D-4. Conclusion**

The residual effective dose arising from living in, on, or near the DARWG locations from May 12, 2011, through March 6, 2012, (300 days) is likely to be comparable to or less than the doses the doses received during the period covered by the OTR, March 12 to May 11, 2011. The thyroid dose arising from the same conditions is likely to be small compared to the dose received during the OTR period and can be neglected for this assessment.

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## **Appendix E.**

### **Dose Coefficients and their Uncertainties**

#### **E-1. Introduction**

The quantities calculated in this report are the effective and organ (thyroid) doses as presented in ICRP Publication 60 (ICRP, 1991) and used in the ICRP databases of DCs (ICRP, 2003a and 2007b).

The DCs from the ICRP database and those based on ICRP models are central estimates; that is, they represent the best estimates. For regulatory purposes and in the development of dose limits, the DCs are considered reference values, fixed and without uncertainty<sup>41</sup> (ICRP, 2007a). The purpose of this report does not include the development of dose limits and regulations but is to estimate radiation doses that are greater than the dose received by any specific person. This requires a consideration of the uncertainty in the DCs used.

#### **E-2. Dose Coefficients Used in this Report**

As discussed in Sections 3.3 and 4.3, the DCs in this report are based on ICRP models and obtained from the ICRP databases of DCs (ICRP, 2003a and 2007b) or from the U.K. Health Protection Agency (Fell, 2012; Smith, 2013). The DCs used for the embryo/fetus and nursing infant dose calculations are shown in Table E-1 and Table E-2.

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<sup>41</sup> The ICRP (2007a) defines a dose coefficient as “a synonym for dose per unit intake of a radioactive substance, but sometimes used to describe other coefficients linking quantities or concentrations of activity to doses or dose rates...” and then goes on to give several examples.

**Table E-1. Inhalation dose coefficients considered in this report**

Radionuclide <sup>*</sup>	Embryo/Fetus (AC+35) <sup>†</sup>		Nursing Infant (AB+1) <sup>†</sup>	
	Effective (nSv Bq <sup>-1</sup> )	Thyroid (nSv Bq <sup>-1</sup> )	Effective (nSv Bq <sup>-1</sup> )	Thyroid (nSv Bq <sup>-1</sup> )
Ba-140	1.4	0.33	0.26	0.026
Cs-134	1.6	1.5	1.5	1.5
Cs-136	0.9	0.90	0.24	0.24
Cs-137	1.1	1.0	1.3	1.2
I-130	2.0	39	1.4	25
I-130, Organic Gas	4.1	81	2.9	53
I-130, Elemental Gas	5.2	100	3.6	67
I-131	21	410	19	400
I-131, Organic Gas	43	840	40	820
I-131, Elemental Gas	55	1100	51	1000
I-132	0.22	4.1	0.063	0.84
I-132, Organic Gas	0.49	9.2	0.14	1.9
I-132, Elemental Gas	0.58	11	0.17	2.2
I-133	4.4	87	3.8	75
I-133, Organic Gas	9.1	180	8	160
I-133, Elemental Gas	12	230	10	200
La-140	0.12	NA <sup>‡</sup>	NA <sup>‡</sup>	NA <sup>‡</sup>
Rb-86	1.0	NA <sup>‡</sup>	NA <sup>‡</sup>	NA <sup>‡</sup>
Mo-99	0.17	0.10	0.0032	0.0022
Tc-99m	0.0064	0.041	0.0068	0.044
Te-129	0.0038	NA <sup>‡</sup>	0.000024	0.00000078
Te-129m	1.2	0.26	0.086	0.21
Te-131m	2.5	46	1.6	33
Te-132	5.9	110	0.39	5.2
Sr-89	8.3	0.25	1.9	0.15
Sr-90	35	1.2	14	0.69

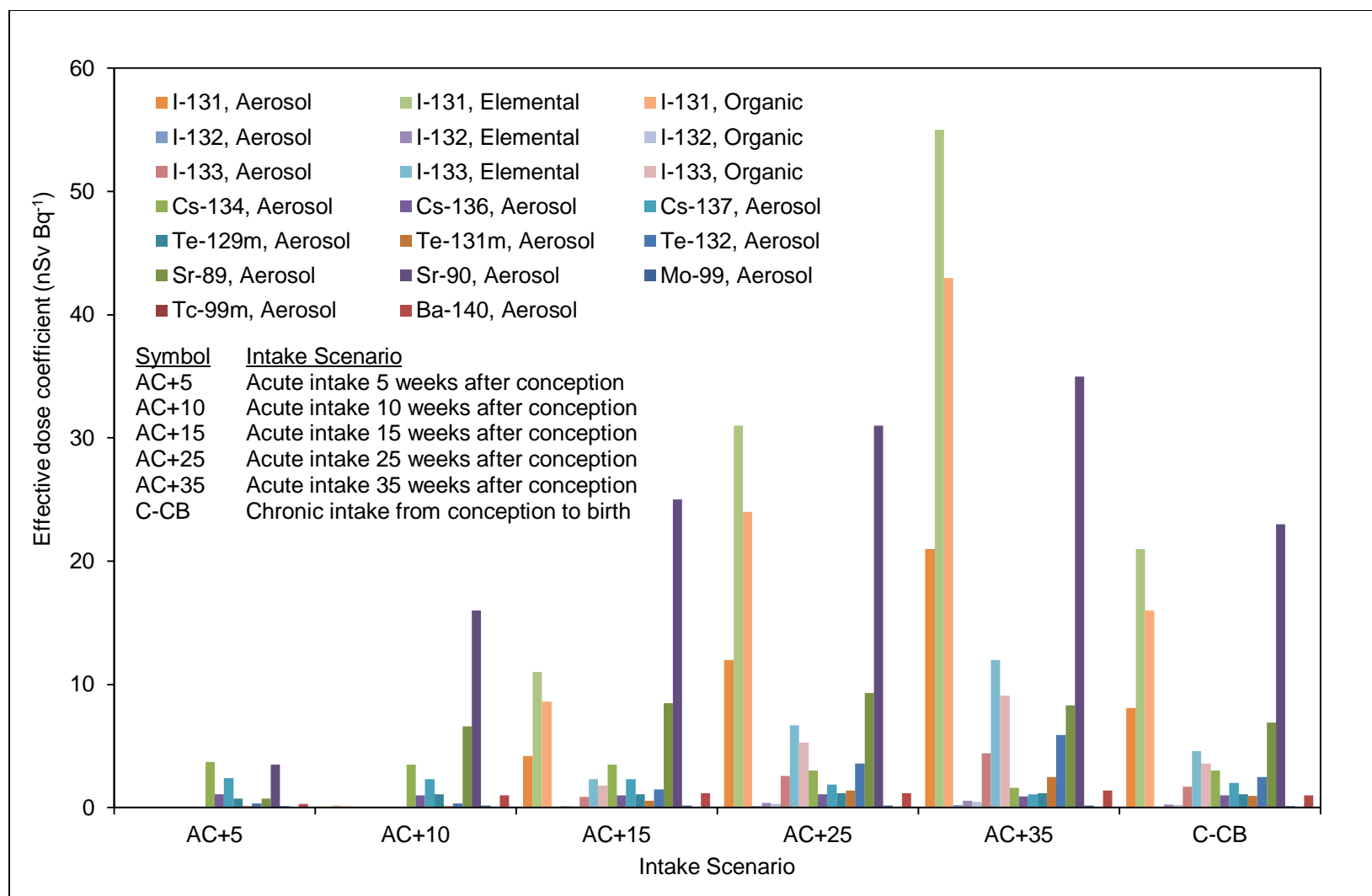
<sup>\*</sup> Type F, 1µm AMAD unless otherwise noted.

<sup>†</sup> These DCs are based on intakes of the mother only.

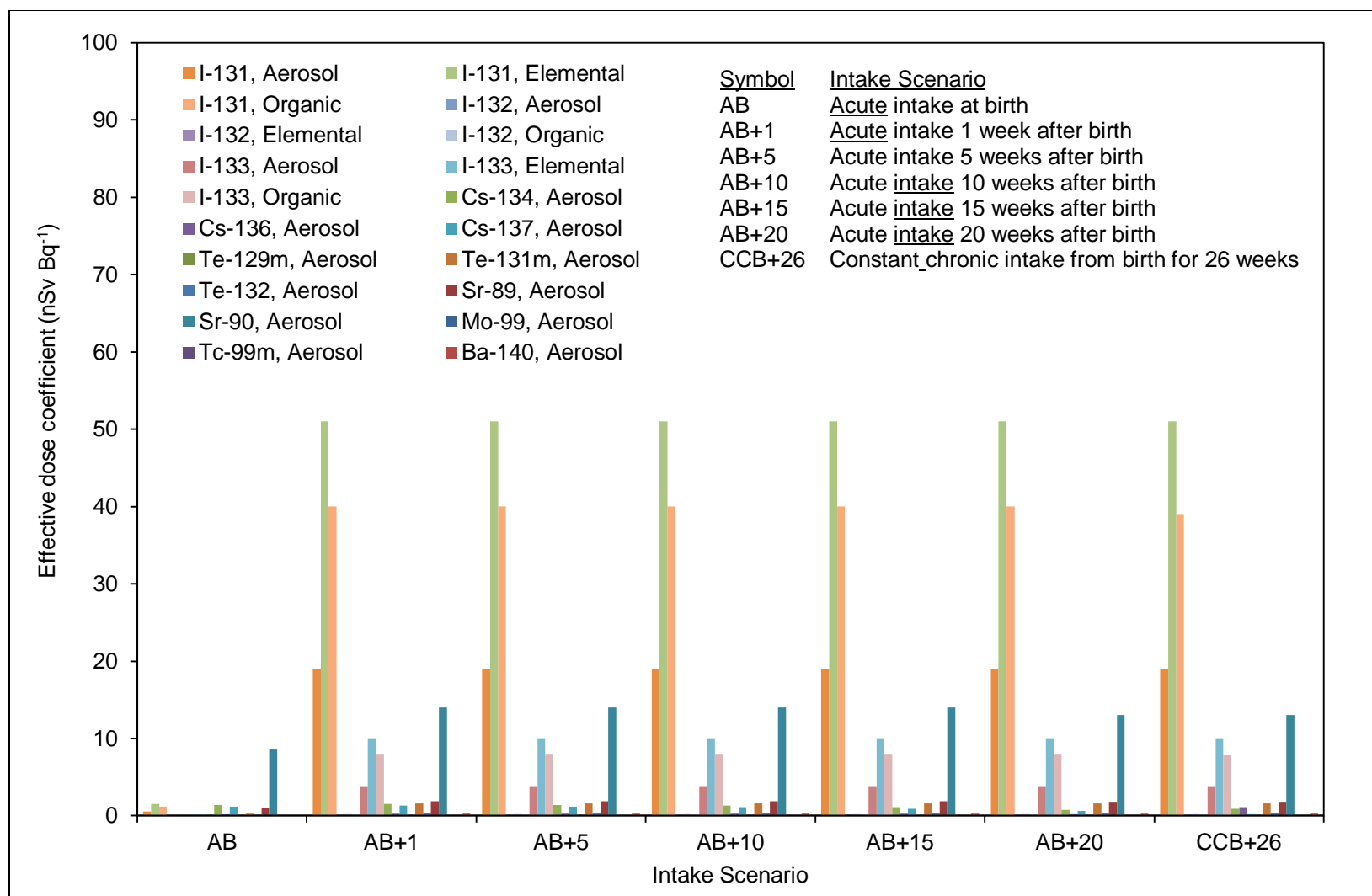
<sup>‡</sup> The DCs for these radionuclides were unavailable at the time of this study.

A bar chart of the embryonic/fetal DCs (effective dose only, but the equivalent dose will follow the same patterns) for all the radionuclides listed in Table 1 except for Te-129, La-140, and Rb-86 is shown below in Figure E-1. Figure E-3 shows the nursing infant effective DCs from inhalation by the mother for all the radionuclides listed in Table 1 except for La-140 and Rb-86. The excluded DCs are not shown in the bar charts because DCs were only available for the AC+35 and AB+1 intake. In the figures below, both elemental and organic (methyl) iodides are gaseous forms of the element.





**Figure E-1. Embryo/fetus effective dose coefficients for inhalation by the mother**



**Figure E-2. Nursing infant effective dose coefficients for inhalation by the mother**

**Table E-2. Ingestion dose coefficients used in the report**

Radionuclide	Embryo/Fetus (AC+35)		Nursing Infant* (AB+1)	
	Effective (nSv Bq <sup>-1</sup> )	Thyroid (nSv Bq <sup>-1</sup> )	Effective (nSv Bq <sup>-1</sup> )	Thyroid (nSv Bq <sup>-1</sup> )
I-131	60	1200	56	1200
Cs-134	4.5	4.5	4.5	4.5
Cs-136	2.6	2.6	0.7	0.7
Cs-137	3.2	3.0	3.8	3.4
Te-132	7.2	130	0.47	6.3

\* These DCs are based on intakes of the mother only.

### E-3. Literature Review for Dose Coefficient Uncertainties

Dunning and Schwartz (1981) discussed the statistical properties of human thyroid anatomy and physiology, I-131 metabolism, and predicted ingestion thyroid dose per unit intake (DPUI) values for newborns, children (0.5–2 y), adolescents (6–16 y), and adults (> 18 y). Their final results are the mode, median, mean, standard deviation, 95<sup>th</sup> and 99<sup>th</sup> percentile values of DPUI values for the age groups under investigation. The value of the GSD derived from the results in Dunning and Schwartz (1981) ranges from 1.78 to 1.98.

As part of the Hanford environmental dose reconstruction project Snyder et al. (1994) developed computer codes to estimate probabilistic radiation doses from atmospheric releases and releases to the Columbia River. Snyder et al. (1994) discussed I-131 ingestion, inhalation, prenatal (embryo/fetus) and nursing infant dose conversion factors with a lognormal distribution. For the inhalation and ingestion dose conversion factors in Snyder et al. (1994) the GSD was assumed to be 2.0 for all ages, based on Dunning and Schwartz (1981). The nursing infant dose conversion factor's GSD was found to be 2.1 based on their analyses (Snyder et al., 1994). For the embryo/fetus, a triangular distribution was assumed because the information on the dose to embryo/fetus from intakes was sparse (Snyder et al., 1994). However, to define the maximum and minimum values of the triangular distribution Snyder et al. (1994) used a GSD of 2.

In 1997, the National Cancer Institute (NCI) published a study that assessed the thyroid doses to the U.S. population from the atomic bomb tests at the Nevada Test Site. Based heavily on Dunning and Schwartz (1981), the NCI (1997) report assumed that the I-131 ingestion DCs for all ages and sexes were lognormally distributed with a GSD of 1.8.

In 1998, the NCRP (1998b) considered the question of the reliability of the DCs based on the models presented in ICRP Publication 30, *Limits for Intakes of Radionuclides by Workers*<sup>42</sup>. To this end, the NCRP (1998b) polled a set of dosimetry experts to obtain “examples of subjective quantification of the reliability” of the DCs for effective dose for a list of radionuclides “assumed to have been released from a nuclear facility and to have been either inhaled or ingested in a soluble form by members of the public.” This list included I-131 and Cs-137, which are of special concern to this report. For an adult male, the DCs for effective dose for both I-131 and Cs-137 were judged to be within a factor of 3 of the true value for 90 percent of the population of adult males. Special populations (diseased people, children, or infants) were

<sup>42</sup> ICRP Publication 30 was published in four parts in 1979.

also considered. For I-131, infants were considered to be the special population; the reliability of the DC for effective dose was judged to be within a factor of three of its true value for 90 percent of the population<sup>43</sup>. For Cs-137, children were considered the special population; the reliability of the DC for effective dose was judged to be within a factor of five of its true value for 90 percent of the population.

Hamby and Benke (1999) performed a probabilistic estimation of the ingestion DC (adult) for I-131. The authors determined that the DC was lognormally distributed with a GSD of 1.19 and had range of about 4 (Hamby and Benke, 1999).

Harrison et al. (2001) reviewed the gastrointestinal absorption for 12 elements, including cesium and iodine. The authors reported (Harrison et al., 2001):

In general, uncertainties in effective dose for children and infants exceeded those in adults as a result of greater uncertainties in  $f_1$  values for the younger age groups. However, this effect was reduced in some cases by shorter retention times of absorbed nuclides in the body tissues and organs.

The ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values for the committed effective dose is reported for adults, a 10 year old child, and a 3 month old infant. According to the authors (Harrison et al., 2001), the square root of this ratio is called an “uncertainty factor” and is equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median) values for a lognormally distributed variable. A given value can be taken to be known within a factor of the UF; for example, if a parameter value is reported to have a UF of 5, then it can be said that the value is known to within a factor of 5 (Harrison et al., 2001).

Fritsch et al. (2003) calculated the distribution of committed equivalent doses to the thyroid for I-131, I-125, and I-129 after an intake of radioactive material. For I-131, the ratio of the 95<sup>th</sup> percentile value to the median value for the equivalent dose to the thyroid was 4.1. Note, the purpose of this study was “to compare uncertainties delivered to the thyroid due to physiological parameters and physical properties of the isotopes after I-131, I-125, or I-129 ingestion at different ages.” (Fritsch, et al., 2003) Note that the calculations do not represent the uncertainty in the DC but only the uncertainty in how much dose is delivered to the thyroid once the iodine enters the thyroid.

Harvey et al. (2003) used a simplified model of iodine metabolism and performed a probabilistic (Latin hyper cube) assessment of the I-131 ingestion DCs for 15 year old males and females, children (10 y, 5 y, and 1 y). The calculations were performed as described in Hamby and Benke (1999). The authors concluded that the DCs were log-normally distributed with age-dependent GSDs; the range of GSDs was 1.55 to 2.61 (Harvey et al., 2003).

Apostoaie and Miller (2004) investigated the uncertainties for the ingestion DCs for I-131, Cs-137, and Sr-90. For infants, the geometric standard deviation (GSD) for the I-131 thyroid DC was found to be 1.8. This corresponds to a ratio of the 95<sup>th</sup> percentile value to the median value of 2.6. For Cs-137 for children, it was reported that uncertainties would be larger

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<sup>43</sup> In Table 8.2 of NCRP (1998b), the infant effective dose DC is placed in category D indicating a “very poorly known value” with a true value possibly outside a factor of 10 of the reported value. The text of the report attributes this to using the adult male DC as the reference point; if the infant DC is used as a reference point, then the DC would have been placed in category A (well known), that is, within a factor of three of its true value.

than for adults:  $GSD > 1.4$  for male children and  $GSD > 1.6$  for female children. These values for the GSDs correspond to a ratio of the 95<sup>th</sup> percentile value to the median value of about 2.

Building on the work of Harvey (2002), Harvey et al. (2006) examined the inhalation DCs for I-131. The authors concluded that the uncertainty in the DCs for I-131 inhalation was lognormal. They presented estimates of the DCs for I-131 “bound to particulates” (Harvey, et al., 2006) and associated uncertainties for mouth and nose breathers separately. The reported GSDs range from 1.57 to 2.21. Harvey (2002), from which Harvey et al. (2006) was derived, presents inhalation DCs and associated uncertainties for I-131 elemental and organic gas; the GSDs for these forms range from 1.56 to 2.23.

Fritsch (2007) compared uncertainties in the ingestion and inhalation DCs for the committed equivalent dose to the thyroid. In his paper, for I-131 ingestion he reports a GSD of 2.61 based on previous work<sup>44</sup> and a GSD of 2.14 for his 2007 work. These correspond to ratios of the 95<sup>th</sup> percentile value to the median value 4.9 and 3.5. For inhalation of I-131, a GSD of 1.66 is reported, which yields a ratio of the 95<sup>th</sup> percentile value to the median value of 2.3. The GSD for inhalation used here does not include a contribution from the individual variability in volume of inhaled air because the DARWG assumes a conservative, fixed value of  $30 \text{ m}^3 \text{ d}^{-1}$  for the maximizing condition for daily inhalation rate (Cassata, et al., 2012).

As part of a review of inhalation doses to military personnel involved with the nuclear weapons tests at the Nevada Test Site, Kocher, et al. (2009) performed a comprehensive evaluation of inhalation DCs reported in the literature. The result of their evaluation was a lognormal uncertainty distribution “relative to dose coefficients for inhalation of radionuclides in respirable or non-respirable oxide form by adult members of the public currently recommended by the ICRP [ICRP, 2001b]” for fission and activation products with a “median of 1.0 and a 90 percent credibility interval between 0.1 and 10.” (Kocher, et al., 2009)

The NCRP (2009b) revisited the issue of uncertainties in DCs with its report, *Uncertainties in Internal Radiation Dose Assessment*. An effort was made to assess the uncertainties in the DCs for a variety of intake scenarios, radionuclide form, and organs. The results were presented as a best estimate, lower bound, and upper bound. The bounding values (NCRP, 2009b) are not “intended as lowest and highest possible values but are meant to represent a likely range based on current information.” Note, there is no statistical meaning attached to the definition. For the thyroid dose from intakes of I-131, the ratio of the upper bound to the best estimate ranges from 1.9 to 2.4 for adult healthy males. Values for the DC for effective dose are not given but are likely to be similar to those given for the DC for the thyroid because the thyroid dose accounts for about 80 percent of the effective dose. For the effective dose from intakes of Cs-137, the ratio of the upper bound to the best estimate ranges from 1.6 to 20 for adult healthy males. The value of 20 is for an acute inhalation and occupational exposure to an unknown form of cesium. If this value is excluded, then the range is 1.6 to 1.8.

Table E-3 summarizes the information on the uncertainties in the DCs (or DPUIs) for I-131, Cs-137, and one example of fission and activation products. The source of the uncertainty information, intake type (ingestion or inhalation), radionuclide, the uncertainty parameter value (e.g., GSD), the UF, and comments are presented. The UF is the square root of the ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values; this is also equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median)

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<sup>44</sup> Fritsch does report the GSD value of 1.8 as found in Apostoaei and Miller (2004).

values reported by the authors or calculated from GSDs if reported. The UF can be calculated as  $(\text{GSD})^{1.65}$ .

**Table E-3. Summary of dose coefficient uncertainties**

Source	Intake Type	Radionuclide	Reported Uncertainty Parameter Value	UF*	Comments
Dunning and Schwartz, 1981	Ingestion	I-131	Mode, median, mean, standard deviation, 95 <sup>th</sup> and 99 <sup>th</sup> percentile values for newborns, children (0.5–2 y), adolescents (6–16 y), and adults (> 18 y)	Adult: 2.7 Adolescent: 2.6 Children: 2.9 Newborn: 3.1	<ul style="list-style-type: none"> <li>• “Thyroid dose equivalent”</li> </ul>
Snyder et al., 1994	Inhalation and Ingestion	I-131	<u>All ages and embryo/fetus</u> GSD = 2.0	3.1	<ul style="list-style-type: none"> <li>• Thyroid and effective dose equivalent</li> <li>• Based heavily on Dunning and Schwartz (1981)</li> </ul>
			<u>Nursing Infant</u> GSD = 2.1	3.4	
NCI, 1997	Ingestion	I-131	<u>All age groups</u> GSD = 1.8	2.6	<ul style="list-style-type: none"> <li>• Thyroid dose</li> <li>• Fetal, infant, child, and adult males and females</li> <li>• Based heavily on Dunning and Schwartz (1981)</li> </ul>
NCRP, 1998b	Inhalation or Ingestion	I-131	Factor of 3 for adult males and children	NA	<ul style="list-style-type: none"> <li>• Committed effective dose</li> <li>• Ratio of a subjective 95 percent credibility limit to the values calculated by the ICRP based on ICRP Publication 30 parameter values</li> </ul>
		Cs-137	Factor of 3 for adult males Factor of 5 for children	NA	

\*The UF is the square root of the ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values; this is also equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median) values reported by the authors or calculated from GSDs if reported.

**Table E-3. Summary of dose coefficient uncertainties (cont.)**

Source	Intake Type	Radionuclide	Reported Uncertainty Parameter Value	UF*	Comments
Hamby and Benke, 1999	Ingestion	I-131	GSD = 1.19	1.33	<ul style="list-style-type: none"> <li>• “Dose to the thyroid”</li> <li>• Range of about 4</li> <li>• Adult</li> </ul>
Harrison et al., 2001	Ingestion	I-131	Adult: 1.05 10 y child: 1.05 3 mo infant: 1.05		<ul style="list-style-type: none"> <li>• Committed effective dose</li> <li>• Adult, 10 y child, 3 mo infant</li> </ul>
		Cs-137	Adult: 1.1 10 y child: 1.1 3 mo infant: 1.05		
Fritsch et al., 2003	Ingestion	I-131	GSD = 2.38	4.18	<ul style="list-style-type: none"> <li>• Committed equivalent dose</li> <li>• Excluding uncertainties in GI tract absorption and thyroid uptake</li> </ul>
Harvey et al., 2003	Ingestion	I-131	<u>Age Group GSD</u> Males 15 y: 1.55 Females 15 y: 1.58 Children 10 y: 1.59 Children 5 y: 1.71 Children 1 y: 1.56 Infants 3 mo: 2.61	2.06 2.13 2.15 2.42 2.09 4.87	<ul style="list-style-type: none"> <li>• “Thyroid dose”</li> </ul>

\* The UF is the square root of the ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values; this is also equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median) values reported by the authors or calculated from GSDs if reported.



**Table E-3. Summary of dose coefficient uncertainties (cont.)**

Source	Intake Type	Radionuclide	Reported Uncertainty Parameter Value	UF*	Comments
Apostoei and Miller, 2004	Ingestion	I-131	<u>Newborn</u> GSD = 1.8	2.6	<ul style="list-style-type: none"> <li>• “Thyroid dose” and equivalent organ doses for Cs-137</li> </ul>
		Cs-137	<u>Children</u> GSD greater than ~1.5	~2.0	
Harvey et al., 2006 Harvey, 2002	Inhalation	I-131	<u>Aerosol GSD Range</u> 1.57 to 2.21	2.10 to 3.70	<ul style="list-style-type: none"> <li>• “Thyroid dose”</li> <li>• Nose breathers and mouth breathers</li> <li>• Age Groups <ul style="list-style-type: none"> <li>○ Males 15 y</li> <li>○ Females 15 y</li> <li>○ Children 10 y</li> <li>○ Children 5 y</li> <li>○ Children 1 y</li> <li>○ Infants 3 mo</li> </ul> </li> </ul>
			<u>Inorganic Gas GSD Range</u> 1.56 to 2.21	2.08 to 3.76	
			<u>Organic Gas GSD Range</u> 1.58 to 2.23	2.13 to 3.76	
Fritsch, 2007	Ingestion	I-131	<u>Previous Work</u> GSD = 2.61	<u>Previous Work</u> 4.87	<ul style="list-style-type: none"> <li>• Committed equivalent dose</li> <li>• Inhalation: 1 µm AMAD, adult male worker</li> </ul>
	Inhalation		<u>Current work</u> GSD = 2.14	<u>Current work</u> 3.51	
			GSD = 1.66	2.08	

\* The UF is the square root of the ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values; this is also equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median) values reported by the authors or calculated from GSDs if reported.

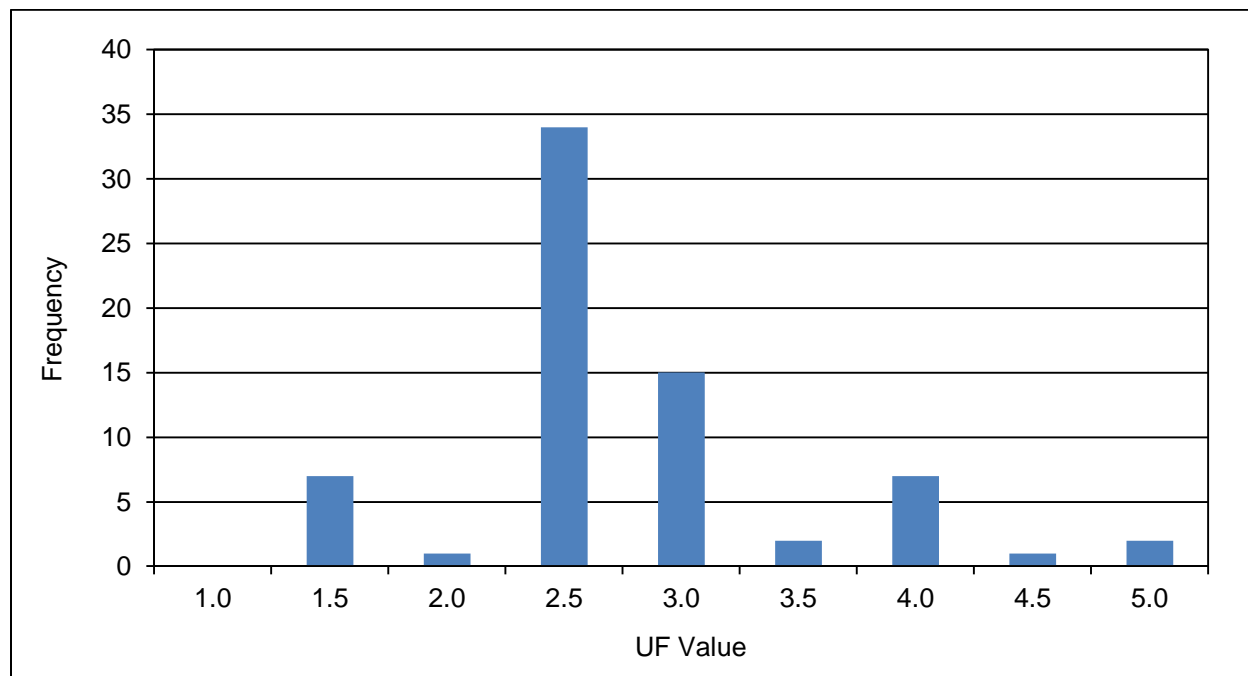
**Table E-3. Summary of dose coefficient uncertainties (cont.)**

Source	Intake Type	Radionuclide	Reported Uncertainty Parameter Value	UF*	Comments
Kocher et al., 2009	Inhalation	Fission and activation products	0.1 to 10	10	<ul style="list-style-type: none"> <li>• Median of 1</li> <li>• 90 percent credibility range</li> <li>• Adults</li> <li>• Includes reviews and summaries of previous work.</li> </ul>
NCRP, 2009b	Inhalation and Ingestion	I-131	1.9 to 2.4	NA	<ul style="list-style-type: none"> <li>• All forms and Types F, M, and S</li> <li>• Committed effective and equivalent doses</li> <li>• Subjective range of upper and lower bounds</li> </ul>
		Cs-137	1.6 to 20 (1.6 to 1.8 excluding the single value of 20 for an unknown form and occupational exposure )	NA	<ul style="list-style-type: none"> <li>• Calculated ratio of upper bound to best estimate</li> <li>• Healthy adult males</li> </ul>

\* The UF is the square root of the ratio of the 95<sup>th</sup> to 5<sup>th</sup> percentile values; this is also equal to the ratio of the 95<sup>th</sup> to 50<sup>th</sup> percentile (median) values reported by the authors or calculated from GSDs if reported.

### E-3.1.1 Discussion of Uncertainty Factors

The data (excluding Kocher et al. (2009) for reasons explained later in this section) in Table E-3 show that the overall mean value for the UF is 2.5 (median = 2.3 range = 1.05–4.87, n = 69) regardless of intake type, age, sex, or radionuclide form. Of the three studies that explicitly examined the DCs for the embryo/fetus and nursing infant, the UFs were reported as 3.1 and 3.4 (Snyder et al. 1994) and 2.6 (NCI, 1997), resulting in a mean value of 3.0 for this group. Figure E-3 shows the distribution of all the UF values.



**Figure E-3. Frequency Distribution of uncertainty factors for dose coefficients**

The UF results from Kocher et al. (2009), although included in the literature review for completeness, are excluded from the final analyses because they are applicable to resuspended fission and activation products from atomic bomb tests whereas this report is concerned with releases from an ongoing nuclear power plant accident. The differences in physical and chemical properties of the radionuclides and types and quantities of radionuclides between FDNPS release and resuspended material from atomic bomb tests are sufficient to conclude that the findings in Kocher et al. (2009) are not appropriate here.

In 1998 and 2009, the NCRP (NCRP, 1998b and 2009b) discussed uncertainties in DCs for various radionuclides, although they did not report UFs as defined here or GSDs of the data. However, the subjective 95 percent credibility limits (values of 3–5) reported in NCRP (1998b) are reasonably conservative approximations of an UF. The NCRP’s “central estimates and plausible ranges” of doses (workers) discussed in NCRP (2009b) can also be viewed as conservative estimates of UFs. The applicable values from NCRP (2009b) for this study range from 1.6 to 2.4.

### **E-3.1.2 Embryo and Fetus**

For the embryo/fetus thyroid dose from intakes of iodine by the mother, the uncertainty in the radiation dose is likely “no greater than the uncertainty in the estimated thyroid dose for postnatal exposures to radioiodines” (Johnson, 1982). The major sources of variation in thyroid dose (hence the DC) including the embryo/fetus are thyroid uptake, biological half time, and thyroid mass (Johnson, 1982, NCI, 1997, and Harvey et al., 2006<sup>45</sup>). Although the values for these parameters can vary widely, they are correlated. For example, an increased thyroid uptake, which in itself would result in a higher dose, might result in a larger thyroid mass, which, in turn, tends to reduce the dose (NCI, 1997). Overall, the correlation between the parameters that most affect the thyroid dose per unit intake tends to move the value of the DC toward its central estimate and reduce the sensitivity of the DC to changes in parameter values (NCI, 1997; Hamby and Benke, 1999; Harvey et al, 2003; and, Harvey et al, 2006).

### **E-3.1.3 Nursing Infant**

Conceptually, the dose to the nursing infant is calculated by estimating the amount of the radionuclide transferred to mother’s milk and then applying the ingestion rate and DC for an infant (3-month old child). The UF in the transfer factor to breast milk was investigated by Simon et al. (2002) and is about 1.7. The UF values for the ingestion DC for an infant are summarized in Section E-3.1.1 as part of the overall discussion of UFs. The additional uncertainty from the transfer factor is not expected to significantly affect the final UF in the dose to a nursing infant.

## **E-4. Conclusion**

The UF is used as the basis for the adjustment factor for the DCs used in these dose assessments to provide an additional margin of confidence that the final radiation doses are likely greater than the actual radiation dose received by any specific embryo/fetus or nursing infant. When setting safety standards, this margin of safety can be determined by the “expected variability of dose and by the potential health risk” (Dunning and Schwartz, 1981). Furthermore, any choice of an UF should be made in light of the choices for all the parameters in the calculations, especially in deterministic calculations. When performing deterministic calculations of the type in this report, choosing high-sided (e.g., upper bounds, 95<sup>th</sup> percentiles, etc.) values for all parameters will result in doses that are unduly conservative. From Figure E-2 it is clear that the majority of UFs fall between 2 and 3 (the mean value is 2.5 for all DC values and 3.0 for the embryo/fetus or nursing infant DC values). A DC adjustment factor of three is judged to be sufficient given the high-sided values chosen for the other parameter values in the dose calculations.

Based on a review of the information in this section, a subjective adjustment factor of three was applied to the DCs for cesium, iodine (all forms), and tellurium used to calculate both the committed effective and thyroid doses for the embryo/fetus. That is, the DCs were multiplied by three in all calculations of internal dose.

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<sup>45</sup> Harvey et al. (2006) account for the effects of thyroid uptake and biological half life in the “time-integrated activity” in their study.

# Abbreviations, Acronyms, and Symbols

AB±X	acute intake at birth ± X weeks (nursing infant doses)
AC±X	acute intake at conception ± X weeks (embryo/fetus doses)
AIPH	Army Institute of Public Health
AMAD	activity median aerodynamic diameter
BIHR	Birth and Infant Health Registry
Bq	becquerel
CCB+26	constant chronic intake from birth to 26 weeks (6 months)
C-CB	chronic intake from conception to birth
CD-ROM	compact disc – read only memory
Ci	curie
CNN	Cable News Network
d	day
DARWG	Dose Assessment and Recording Working Group
DC	dose coefficient
DOD	Department of Defense (United States)
DPUI	dose per unit intake
DTRA	Defense Threat Reduction Agency
E	effective dose
EDE	effective dose equivalent
EPA	Environmental Protection Agency (United States)
FAO	Food and Agriculture Organization of the United Nations
FDNPS	Fukushima Daiichi Nuclear Power Station
GSD	geometric standard deviation
Gy	gray
H	equivalent dose
h	hour
HADR	humanitarian assistance and disaster relief
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
J	joule
kg	kilogram
km	kilometer
$\lambda$	physical (radiological) decay constant
L	liter
m	meter
MCAS	Marine Corps Air Station (United States)
MEXT	Ministry of Education, Culture, Sports, Science, and Technology (Japan)
mg	milligram
min	minute
ml or mL	milliliter
mo	month(s)
NAF	Naval Air Facility (United States)

NAS	National Academy of Sciences (United States)
NCI	National Cancer Institute (United States)
NCRP	National Council on Radiation Protection and Measurements (United States)
NHK	Japan Broadcasting Corporation's identification to English speaking audiences by the pronunciation of the initials N-H-K.
NIH	National Institutes of Health
OT	Operation Tomodachi
OTR	Operation Tomodachi Registry
PEP	potentially exposed population
POI	population of interest
SI	International System of Units (from the French <i>Système International d'Unités</i> )
SM	standard method
SOP	standard operating procedure
Sv	sievert
TED	total effective dose
TR	technical report
UF	uncertainty factor
U.K.	United Kingdom (United Kingdom of Great Britain and Northern Ireland)
U.S.	United States
USGS	United States Geological Survey
WHO	World Health Organization
y	year